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Abstract The ability to minimize potato yield and quality losses due to drought can be greatly improved by understanding the relative responses of different cultivars to seasonal variations in water supply. To address this need, we initiated a 2 year field experiment to determine the responses of the six potato cultivars to different seasonal drought patterns, including 1) full season irrigation at 100 % ET, 2) irrigation at 100 % ET terminated during late bulking , 3) full season irrigation at 70 % ET , 4) irrigation at 70 % ET terminated during late bulking , and 5) a gradual reduction in irrigation from 100 % ET during tuber initiation through early bulking, to 70 % ET during mid-bulking, and 50 % ET through late bulking. GemStar Russet and Ranger Russet, two medium-late maturing cultivars, generally produced the highest yields across the range of drought treatments, but both were fairly sensitive to changes in drought severity. Alturas, a late maturing cultivar, produced relatively high yields with full irrigation, but exhibited the greatest sensitivity to increasing drought severity, particularly when severe late-season water deficits were imposed. Yields for the early maturing cultivar Russet Norkotah were relatively low overall, but it was the least sensitive to changes in drought severity, particularly when late season drought was imposed. Russet Burbank produced comparatively high total yields across the range of drought treatments, but U.S. No. 1 yields were substantially reduced by each seasonal drought pattern. However, it was less sensitive to changes in drought severity than GemStar Russet, Ranger Russet and Alturas. Total and U.S. No. 1 yields for Summit Russet were low for each drought treatment and it exhibited intermediate sensitivity to changes in drought severity. GemStar Russet had the highest water use efficiency based on U.S. No. 1 yield.

Resumen Se puede mejorar grandemente la habilidad para minimizar las pérdidas en rendimiento y calidad de papas debido a la sequía, mediante el entendimiento de las respuestas relativas de diferentes variedades a variaciones estacionales en el suministro de agua. Para atender esta necesidad, iniciamos un experimento de campo por dos años para determinar las respuestas de seis variedades de papa a diferentes patrones de sequía estacional, incluyendo, 1) riego completo en el ciclo al 100 % ET, 2) riego al 100 % ET terminando durante el fin de la tuberización, 3) riego durante todo el ciclo a 70 % ET, 4) riego al 70 % ET terminando al final de la tuberización, y 5) reducción gradual de riego de 100 % ET durante la iniciación de la tuberización a lo largo del llenado temprano, a 70 % ET durante la mitad del llenado, y 50 % ET a lo largo de la tuberización tardía. Gem Star Russet y Ranger Russet, dos variedades de intermedias a tardías, generalmente produjeron los rendimientos más altos a lo largo de la amplitud de los tratamientos de sequía, pero ambas fueron muy sensibles a los cambios de la severidad de la sequía. Alturas, una variedad tardía, produjo rendimientos relativamente altos con riego completo, pero exhibió la mayor susceptibilidad al aumento en la severidad de la sequía, particularmente cuando se impuso déficit hídrico severo al final del ciclo. Los rendimientos de la variedad temprana Russet Norkotah fueron relativamente bajos en general, pero fue la menos sensible a los cambios en la severidad de la sequía, particularmente cuando se le exponía al final del ciclo. Russet Burbank produjo comparativamente altos rendimientos totales ante la amplitud de los tratamientos de sequía, pero se redujeron

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substancialmente los rendimientos de U.S. No. 1 por cada patrón estacional de sequía. No obstante, fue menos sensible a cambios en la severidad de sequía que Gen Star Russet, Ranger Russet y Alturas. Los rendimientos totales de U.S. No. 1 para Summit Russet fueron bajos en cada tratamiento y exhibió sensibilidad intermedia a cambios en severidad de sequía. Gem Star Russet tuvo la más alta eficiencia en el uso del agua con base al rendimiento de U.S. No. 1.

Keywords *Solanum tuberosum* · Variety · Irrigation · Water stress · Water use efficiency

Introduction

Potato is a relatively drought-sensitive crop (van Loon 1981; Jefferies and MacKerron 1987) for which soil water content needs to be maintained within a relatively narrow range throughout the growing season for maximum yield and quality (Wright and Stark 1990; King and Stark 1997). As a result, potato production in arid regions is highly dependent on irrigation water supplies to produce high yields of marketable potatoes.

In much of the western U.S., the amount of rain and snow during the winter and spring months has a marked effect on irrigation water supplies and can vary greatly from year to year. Concerns regarding the sustainability of water supplies in many of the aquifers in the western U.S. have also increased in recent years. Advances in irrigation science and hydrologic modeling have provided useful options for developing appropriate management strategies for potato cropping systems during periods of drought (King et al. 2004). However, a grower's ability to make field-specific management decisions to minimize the effects of drought can be greatly improved by understanding the relative responses of different cultivars to seasonal variations in water supply.

Studies have been conducted in many potato growing regions of the world to evaluate responses of potato cultivars to water deficits imposed at various growth stages. The results of these studies show that potato response to drought varies widely among cultivars (Martin and Miller 1983; Wolfe et al. 1983; Stark et al. 1991; Shock and Feibert 2002) and also differs according to the extent and timing of the water deficits (Miller and Martin 1987; Lynch and Tai 1989; Stark and McCann 1992; Lynch et al. 1995; Ierna and Mauromicale 2006).

Characterization of drought tolerance in potato cultivars is complicated by the fact that differential yield responses have not been consistently related to specific physiological or morphological traits. Haverkort and Goudriaan (1994) suggested that early developing potato cultivars may avoid drought by completing tuber growth before late season drought develops. However, data supporting validation of this hypothesis is limited (Lynch and Tai 1989; Deblonde et al. 1999). Part of the difficulty in identifying specific factors associated with drought susceptibility is related to the fact that timing and severity of drought is often difficult to impose and maintain under field conditions.

Steckel and Gray (1979) examined rooting depth and soil water extraction of potato cultivars differing in drought susceptibility and found that these parameters could not be consistently related to yield responses under varying soil moisture conditions. Stark et al. (1991) evaluated the canopy temperatures of 14 potato genotypes under water-stressed and well-watered conditions and found that the most drought tolerant genotypes had the warmest canopy temperatures under well-watered conditions, indicating reduced transpiration rates. They concluded that the ability of drought tolerant potato genotypes to maintain adequate transpiration during drought was due in part to a greater ability to conserve soil water when conditions were optimal.

Many of the potato cultivars currently grown in North America have not been evaluated for their response to water deficits imposed during different periods of the growing season. To address this need, we initiated a 2-year field experiment to determine the responses of the six potato cultivars with widely differing growth characteristics to different seasonal drought patterns. The experiments were conducted under conditions with very limited rainfall, which provided a high degree of control over the distribution of seasonal water supplies.

Materials and Methods

The experiment was conducted in 2002 and 2003 at the University of Idaho Research & Extension Center at Aberdeen on a Declo sandy loam soil. The experimental design was a split-plot, randomized complete block with five replications. The main plot treatments consisted of five seasonal water allocation patterns including 1) full season irrigation at 100 % evapotranspiration [ET] (100 % ET full season), 2) irrigation at 100 % ET until the beginning of late tuber bulking (August 10) when irrigation was terminated (100 % ET early termination), 3) full season irrigation at 70 % ET (70 % ET full season) , 4) irrigation at 70 % ET until the beginning of late bulking (August 10) when irrigation was terminated (70 % ET early termination), and 5) a gradual reduction in irrigation amounts from 100 % ET during early bulking, beginning at tuber initiation through July 15, to 70 % ET during mid bulking from July 15 through August 10, and 50 % ET through the end of late bulking (100/70/50 % ET). The average tuber initiation date for the six cultivars was June 22 in 2002 and June 27 in 2003. Tuber initiation was defined as having 50 % of the tubers >10 mm. Evapotranspiration was estimated with a modified Penman method (Wright 1982), using data provided by an AgriMet weather station (U.S. Bureau of Reclamation, Boise Idaho) located within 500 m of the research plots. Drought treatment main plots were 12 m wide and 24 m long and were irrigated with a solid-set sprinkler system positioned along the outer perimeter of each main plot. Plots were irrigated at 3 to 5 day intervals and differences in irrigation amounts were produced by adjusting the run time of the irrigation set.

Water application amounts were recorded by collecting water in two rain gauges; one placed in the center of each half of the main plots. Soil water content in the top 60 cm of soil in each plot was determined gravimetrically from a composited three-core sample 2–3 days prior to emergence and 1 week prior to harvest. The change in soil water content between the beginning and end of the growing season was added to cumulative water application totals for each plot to develop an estimate of seasonal water use.

Each main plot was comprised of 6 cultivar sub-plots, 3.6 m (4 rows) wide × 12 m long, planted in 0.9 m-wide rows. All cultivars were planted using a two-row planter on May 7, 2002 and May 6, 2003. Seed pieces were planted 35 cm apart at a depth of 15–20 cm. The six cultivars included Russet Burbank, Alturas (Novy et al. 2003), GemStar Russet (Love et al. 2006), Ranger Russet (Pavek et al. 1992), Summit Russet (Love et al. 2005) and Russet Norkotah (Johansen et al. 1988). These six cultivars represent a very wide range of seasonal growth patterns and water requirements. Russet Burbank is a late maturing cultivar with a relatively high water requirement and is considered as highly sensitive to water deficits. Alturas is also late maturing and produces large, vigorous vines that significantly increase the water requirement late in the growing season. Seasonal water requirements for Alturas are typically 15–20 % greater than Russet Burbank (Novy et al. 2003). Ranger Russet is a medium-late maturing cultivar that exhibits rapid, early-season growth, but is susceptible to early season water deficits. GemStar Russet is also a medium-late maturing cultivar but is notable for its tolerance to drought (Love et al. 2006). Russet Norkotah is an early maturing cultivar with a relatively weak root system, while Summit Russet tends to emerge slowly, and bulks tubers very late in the season, making it potentially sensitive to late season water stress.

All fertilizers and pesticides were applied according to University of Idaho guidelines. Vines were mechanically removed on Sept. 12, 2002 and Sept. 16, 2003 with a rotary vine beater. On Sept. 26, 2002 and Sept. 30, 2003, two 10-m sections of row were harvested from the middle two rows in each plot. Tubers were sorted, graded and weighed and a 10-kg sub-sample from each plot was used to determine specific gravity by the weight-in-air/weight-in-water method (Kleinschmidt et al. 1984). U.S. No. 1 yields were defined as tubers with diameters greater than 48 mm and less than 5 % internal and external defects. Yield, quality and water use data were analyzed using the PROC MIXED procedure in SAS software Version 9.2 (2008 SAS Institute, Cary NC, USA). Water use efficiency (kg tuber fresh weight produced per mm of water used) was calculated by dividing the fresh yield of tubers by the sum of irrigation water applied plus the change in soil water content at the 0–60 cm depth. This approach for estimating ET assumes that percolation of water below the 60 cm depth was negligible.

Results and Discussion

Precipitation during the growing season was less than 50 mm in both 2002 and 2003, providing ideal conditions for imposing the different drought treatments (Table 1). Beginning volumetric soil water content ranged from 20.6 to 23.5 % in 2002 and from 21.4 to 22.7 % in 2003. Soil water content just prior to harvest ranged from 16.3 to 19.7 % in 2002 and from 15.8 to 20.1 % in 2003.

Overall, monthly temperature means were similar for the 2 years of the study, although maximum temperatures for July and August were slightly higher in 2003. Estimated ET for the growing season was also about 10 % higher in 2003 than 2002 (Figs. 1 and 2).

Cumulative water application totals (irrigation + precipitation) for the 100 % ET and 70 % ET treatments were close to their respective target amounts in both 2002 and 2003. Total seasonal ET was 580 mm in 2002 and 635 mm in 2003. For the 100 % ET full season, 100 % ET early termination, 70 % ET full season, 70 % ET early termination and 100-70-50 % ET treatments, water application totals were 580, 398, 397, 300 and 380 mm in 2002 and 606, 390, 449, 301 and 433 mm in 2003, respectively. Relative to total seasonal ET requirements, these amounts corresponded to 96–100 % ET for the 100 % ET full season treatment, 64–69 % ET for the 100 % ET early termination treatment, 69–74 % ET for the 70 % ET full season treatment, 50–52 % ET for the 70 % ET early termination treatment and 65–71 % ET for the 100-70-50 % ET treatment.

Although there were some small deviations from the intended water application amounts between years, the resulting wide range of seasonal water distribution patterns provided an excellent opportunity to evaluate cultivar responses to different drought scenarios. The widely divergent irrigation patterns produced highly significant treatment effects for irrigation treatment and cultivar as well as significant treatment interactions for year × cultivar and irrigation × cultivar (Table 2). The year × irrigation × cultivar interaction was significant for percent U.S. No. 1 yield and yield of U.S. No. 1 tubers > 340 g.

Drought treatment main effects show that the 70 % ET early termination treatment produced the greatest reductions

Table 1 Monthly means for daily minimum, maximum and mean temperatures, and total monthly precipitation (PPT) in 2002 and 2003

Month	Min temp °C		Max temp °C		Mean temp °C		PPT mm	
	2002	2003	2002	2003	2002	2003	2002	2003
May	3.3	5.2	19.8	20.3	11.6	12.7	14	11
June	8.5	7.6	24.0	25.3	16.3	16.5	4	5
July	12.1	11.3	30.9	32.6	21.5	21.9	11	0
Aug	7.4	10.9	27.6	31.1	17.5	21.0	0	15
Sept	6.4	4.0	22.7	22.6	14.6	13.3	16	7

PPT monthly precipitation

in total yield and U.S. No. 1 yield, reducing total yields by 34 %, U.S. No. 1 yields by 43 %, and yield of tubers > 340 g by 76 % compared to the 100 % ET full season treatment (Table 3). The 100-70-50 % ET treatment produced higher U.S. No. 1 yields than each of the other three stress treatments, but yields were still considerably lower than the 100 % ET full season treatment. Since the water application totals for the 100/70/50 % ET treatment were slightly lower than those for the 70 % ET full season treatment, it appears that, for an equivalent seasonal water supply, an irrigation strategy that gradually reduces water availability throughout tuber bulking will provide a better opportunity for the crop to acclimate to drought than full season stress.

Specific gravity was increased by both of the early irrigation termination treatments, which is often observed with tubers exposed to water deficits late in the growing season (Stark and Love 2003). As the soil dries, transpiration exceeds root water uptake for a period of time as the plants adjust to developing drought, thereby reducing tuber water content and increasing specific gravity. In contrast, water deficits imposed during early tuber development, such as in the 70 % ET full season and 70 % ET early termination treatments, typically decrease tuber specific gravity compared to well-watered plants (Miller and Martin 1987; Stark and McCann 1992).

Cultivar main effect means show substantial differences in tuber yield potential averaged across the range of drought treatments (Table 3). GemStar Russet and Ranger Russet produced the highest mean total yields, followed by Russet Burbank, Alturas, Russet Norkotah and Summit Russet. U.S. No. 1 yield results were somewhat different, with GemStar Russet producing significantly higher mean yields than any other cultivar, while Russet Burbank yields were clearly the lowest. Mean U.S. No. 1 yields for the other four cultivars fell within a 4.5 $Mg ha^{-1}$ range. Yields of large (>340 g) U.S. No. 1 tubers were much higher for GemStar Russet than any of the other cultivars followed by Ranger Russet.

The potato cultivars used in this study responded very differently to the various drought patterns (Tables 4 and 5). GemStar Russet and Ranger Russet produced the highest total yields in 2002 when irrigated during the entire season at 100 % ET. Alturas and Russet Burbank yields were lower with optimal water supplies than GemStar Russet but were similar to Ranger Russet. Russet Norkotah and Summit Russet produced the lowest total yields with full irrigation.

When irrigation at 100 % ET was abruptly terminated on August 10 in 2002, GemStar Russet and Ranger Russet produced higher total yields than all other cultivars except Russet Norkotah. However in 2003, all cultivars yielded similarly for the 100 % ET early termination treatment,

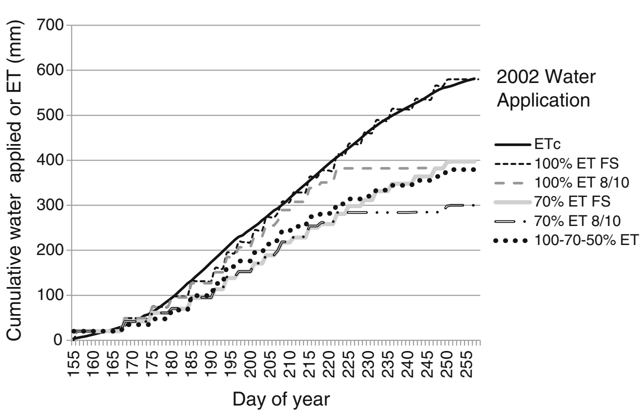

Fig. 1 Cumulative ET and water application (irrigation + precipitation) amounts for each drought treatment in 2002

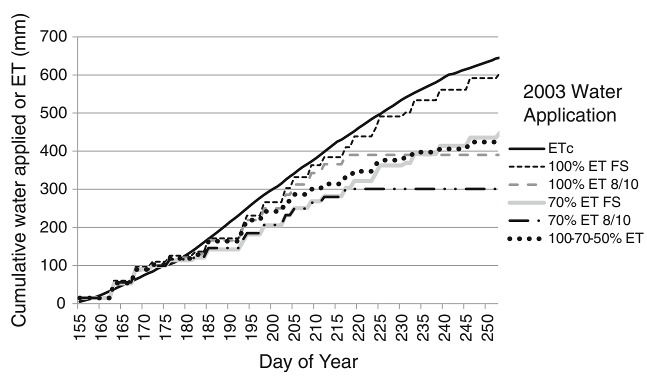

Fig. 2 Cumulative ET and water application (irrigation + precipitation) amounts for each drought treatment in 2003

Table 2 Analysis of variance for treatment effects on total yield, U.S. No. 1 yield, large (>340 g) US No. 1 tuber yield, and specific gravity in 2002–2003

Source	*F*-value					
	DF	Total yield	US no. 1	% US no.1's	>340 g yield	Specific gravity
Year	1	0.59 ns	0.96 ns	0.56 ns	286.0 ***	99.7 ***
Drought treatment	4	27.6 ***	19.1 ***	8.85 ***	31.4 ***	30.6 ***
Year × drought treatment	4	2.4 ns	1.97 ns	1.81 ns	6.22 ***	1.89 ns
Cultivar	5	72.7 ***	61.3 ***	135.1 ***	60.1 ***	310 ***
Year × cultivar	5	3.41 **	5.4 ***	4.32 ***	65.6 ***	14.4 ***
Drought × cultivar	20	3.38 ***	3.16 ***	2.38 **	3.4 ***	2.9 ***
Year × drought × cultivar	20	1.11 ns	1.41 ns	2.09 **	1.76 *	1.02 ns

*, **, *** indicate significance at p=0.05, 0.01 and 0.001, respectively; *ns* not significant

except for Summit Russet, which produced lower total yields than all other cultivars except Russet Norkotah.

When drought stress was imposed for the entire season in 2002 by restricting irrigation to 70 % ET, GemStar Russet produced the highest total yields along with Ranger Russet, while Russet Norkotah and Summit Russet yields were significantly lower than the other four cultivars. In 2003, total yield for Ranger Russet with the 70 % ET full season treatment was higher than all other cultivars except Russet Burbank, although Russet Burbank was not significantly different from the other four cultivars.

When irrigation at 70 % ET was terminated on August 10 in both 2002 and 2003, GemStar Russet, Ranger Russet, Russet Burbank and Russet Norkotah produced similar total yields, while Alturas yields were generally lower. Summit Russet produced reasonably good yields under this severe drought treatment in 2003 but yields were substantially reduced in 2002.

The 100-70-50 % ET treatment was imposed to assess the different cultivar's ability to adjust to gradually developing drought. Under these conditions, GemStar Russet and Ranger Russet produced higher total yields than all other cultivars except Russet Burbank in 2002 and 2003. Summit Russet produced the lowest total yields with the 100-70-50 % ET treatment, while yields for Alturas and Russet Norkotah were intermediate.

With respect to general trends in total yield response to drought, GemStar Russet and Ranger Russet exhibited the greatest resistance to drought overall and responded similarly across the range of seasonal drought treatments. Russet

Table 3 Drought treatment and cultivar main effects on yield, grade and specific gravity for 6 potato cultivars grown at Aberdeen ID in 2002 and 2003

	Total yield ($Mgha^{-1}$)	US no. 1 yield ($Mgha^{-1}$)	Percent US no. 1's	>340 g yield ($Mgha^{-1}$)	Specific gravity
Drought treatment main effects					
100 % ET full season	40.09	28.56	71.3	8.94	1.083
100 % ET early termination	31.49	22.36	70.8	5.17	1.090
70 % ET full season	33.08	22.44	67.9	5.45	1.083
70 % ET early termination	26.47	16.32	61.0	2.13	1.091
100-70-50 gradual drought	34.13	24.65	72.5	5.87	1.088
LSD 0.05	1.36	1.45	2.6	0.80	0.001
Cultivar main effects					
Alturas	32.49	22.44	67.4	3.84	1.093
Gem Star Russet	37.43	29.93	78.9	10.73	1.090
Ranger Russet	37.54	24.94	65.7	6.06	1.094
Russet Burbank	35.03	16.54	46.7	3.83	1.077
Russet Norkotah	29.80	22.89	76.2	3.76	1.073
Summit Russet	26.02	20.45	77.5	4.85	1.094
LSD 0.05	1.49	1.59	2.9	0.87	0.001

Table 4 Drought treatment effects on total and U.S. no. 1 yields of six potato cultivars in 2002

Cultivar	Drought treatment									
	100 % ET full season		100 % ET early termination		70 % ET full season		70 % ET early termination		100/70/50 %ET gradual drought	
	Total yield	US#1 yield	Total yield	US#1 yield	Total yield	US#1 yield	Total yield	US#1 yield	Total yield	US#1 yield
	($Mgha^{-1}$)									
GemStar Russet	50.2	40.5	36.5	30.6	42.7	36.2	28.7	22.3	40.2	33.3
Alturas	43.5	35.5	31.1	22.1	33.4	23.1	21.7	11.6	35.3	26.8
Ranger Russet	45.8	33.1	36.6	24.4	40.9	22.0	26.5	14.0	40.2	29.1
Russet Burbank	45.3	20.6	31.8	17.3	35.5	12.3	27.9	11.0	38.3	19.1
Russet Norkotah	34.1	27.1	33.4	27.4	26.6	19.9	25.2	19.0	31.6	25.4
Summit Russet	31.7	26.9	24.6	19.9	24.6	18.9	17.4	11.3	27.6	21.8
LSD 0.05	4.8	5.6	4.0	4.1	3.6	4.2	4.1	5.6	3.6	4.9

Burbank produced reasonably good total yields in response to drought that were only slightly lower than GemStar Russet Burbank and Ranger Russet. Alturas performed reasonably well with adequate water supplies, but total yields were reduced considerably by late season drought. Russet Norkotah yields were lower than the late-season cultivars overall, but the only appreciable reductions relative to full irrigation occurred in response to full-season drought in 2002. Summit Russet produced the lowest total yields overall, but showed a greater susceptibility to late-season drought than Russet Norkotah in 2002.

Irrigation treatment effects produced proportionately larger differences in U.S. No. 1 yield of the six cultivars than total yield (Tables 4 and 5). GemStar Russet produced U.S. No. 1 yields that were equal to or greater than any other cultivar with each of the five drought treatments. As with all of the cultivars in this study, GemStar Russet experienced the greatest yield reductions with the 70 % ET early termination treatment. However, it performed much better when drought was imposed more gradually in the 100-70-50 % ET treatment.

U.S. No. 1 yields for Ranger Russet were lower than GemStar Russet for all treatments in 2002 except the 100-70-50 % ET treatment. But in 2003, U.S. No. 1 yields for these two cultivars were generally similar. As observed for GemStar Russet, U.S. No. 1 yield reductions for Ranger Russet were greatest with the 70 % ET early termination treatment but it also adjusted well to gradually developing drought imposed with the 100-70-50 % ET treatment.

Alturas yields were lower than GemStar Russet for all of the drought treatments in 2002 and for the 70 % ET early termination and 100-70-50 % ET treatments in 2003. Alturas U.S. No. 1 yields were extremely sensitive to severe late-season drought as evidenced by the substantial yield

Table 5 Drought treatment effects on total and U.S. No. 1 yields of six potato cultivars in 2003

Cultivar	Drought treatment									
	100 % ET full season		100 % ET early termination		70 % ET full season		70 % ET early termination		100/70/50 %ET gradual drought	
	Total yield	US#1 yield	Total yield	US#1 yield	Total yield	US#1 yield	Total yield	US#1 yield	Total yield	US#1 yield
	($Mgha^{-1}$)									
GemStar Russet	42.8	35.1	33.4	26.9	32.0	24.1	31.4	21.8	36.5	28.5
Alturas	41.6	27.5	31.1	22.8	31.9	21.8	24.2	11.4	31.0	21.8
Ranger Russet	45.6	30.7	33.3	21.1	39.0	27.8	30.1	19.9	37.5	27.3
Russet Burbank	38.2	18.9	31.8	14.2	33.5	17.6	32.7	15.8	35.3	18.7
Russet Norkotah	30.6	22.8	28.8	21.0	28.4	21.9	28.3	21.0	30.8	23.5
Summit Russet	31.7	24.1	25.6	20.6	28.4	23.7	26.6	16.7	25.1	20.6
LSD 0.05	6.4	6.7	4.9	4.7	5.9	6.8	6.4	5.5	5.4	4.8

reductions with the 70 % ET early termination treatment. As previously mentioned, Alturas produces a large vigorous vine, which remains active late in the growing season thereby increasing late-season water requirements (Novy et al. 2003).

In 2002, exposure to continual drought stress in the 70 % ET full season and 70 % ET early termination treatments produced marked reductions in Russet Norkotah U.S No. 1 yields. However, late-season drought imposed following normal early-season irrigation levels in the 100 % ET early termination and 100-70-50 % ET treatments had little effect on yield since tuber bulking was apparently nearly complete by the time drought was imposed. Summit Russet U.S. No. 1 yields were comparatively low overall but were generally reduced more by the early termination treatments than the gradual drought treatment.

Russet Burbank produced low U.S. No. 1 yields with all irrigation treatments, particularly with the 100 % ET early termination and the 70 % ET full season treatments. The 100-70-50 % ET treatment appeared to give Russet Burbank the best opportunity to adjust to drought, as it did with most of the other cultivars. The observation that Russet Burbank is less sensitive to late season drought than early season drought was previously reported by Stark and McCann (1992).

Other investigators have also reported differential responses of potato cultivars to water stress timing. Miller and Martin (1987) and Lynch and Tai (1989) evaluated cultivar responses to moisture stress at different growth stages and concluded that Russet Burbank exhibited a strong sensitivity to stress at tuber initiation, compared to a number of other cultivars, particularly with respect to marketable yield. Lynch et al. (1995) determined responses of 8 potato cultivars to a single transient period of drought stress imposed during the early, mid and late portions of the growing season. They reported that Atlantic and Conestoga were more sensitive to early and midseason drought stress than Ranger Russet, Russet Burbank, and several other cultivars. In our study, drought stress produced a marked reduction in Russet Burbank U.S. No. 1 yield compared to other cultivars regardless of stress timing, while Ranger Russet was able to maintain higher U.S. No. 1 yields when exposed to drought..

To illustrate the relative sensitivity to changes in drought severity of the six cultivars, mean total and U.S. No. 1 yields for each cultivar were plotted as a function of the corresponding mean total or U.S. No. 1 yield for all six cultivars for each corresponding drought treatment (Fig. 3). This approach for evaluating yield stability of crop genotypes across different environments is similar to that used by Finlay and Wilkinson (1963) and Eberhart and Russell (1966). Linear regressions describing the drought responses for the six cultivars were significantly different at $P<0.001$ for both total (Fig. 3a) and U.S. No. 1 (Fig. 3b) yields.

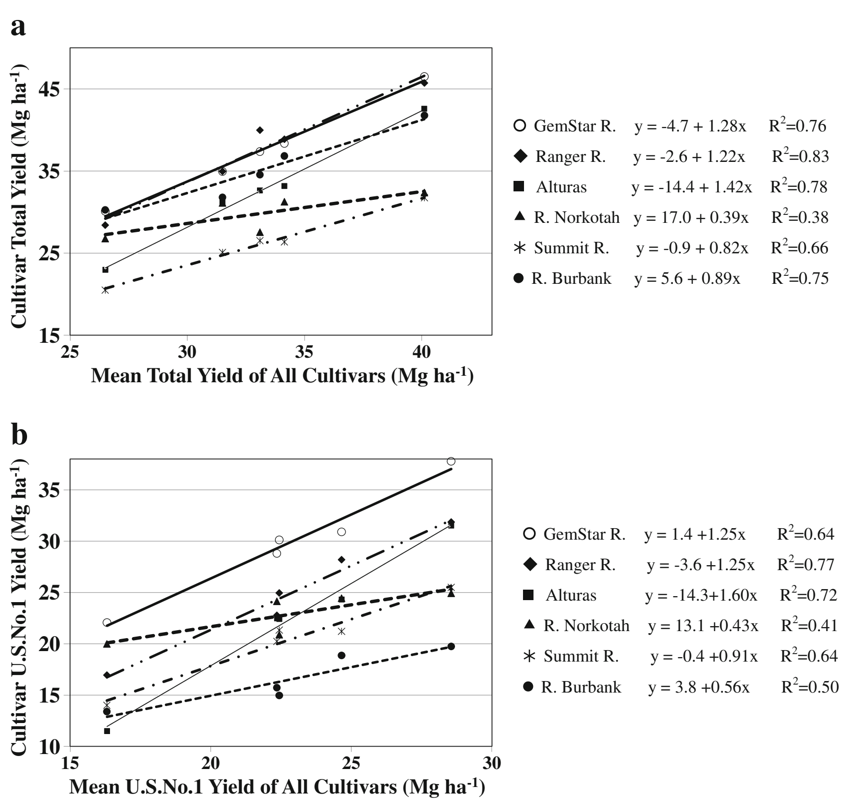

Fig. 3 Mean total yield (**a**) and U.S. No. 1 yield (**b**) for each cultivar plotted as a function of the mean yield for all six cultivars for each drought treatment. Data points represent the average of treatment means for 2002 and 2003. Linear regression equations for the six cultivars were significantly different at $P<0.001$

Although total yields were relatively high, the slopes of the total yield regression lines for GemStar Russet and Ranger Russet were among the highest in the group, with both exhibiting relatively high sensitivity to changes in drought severity (Fig. 3a) The slopes of the U.S. No. 1 regression lines for GemStar and Ranger Russet were also similarly high , with again both showing relatively high sensitivity to increasing drought severity. Total and U.S. No. 1 yield regression lines for Alturas were the steepest among all the cultivars, indicating that it had the highest sensitivity to increasing drought stress.

In contrast, the slopes of the total and U.S. No. 1 regression lines for Russet Norkotah were the lowest of all the cultivars, showing that it was the least sensitive to differences in drought severity. The earlier development of Russet Norkotah apparently allowed it to largely avoid the effects of drought by completing most of its tuber growth before soil water deficits became severe.

Total and U.S. No. 1 regression lines for Russet Burbank also had relatively low slopes, indicating lower sensitivity to changes in drought severity, but its U.S. No. 1yields were lower than nearly every other cultivar. Summit Russet had a more moderate response to changes in yield potential associated with increasing water supply, indicating intermediate sensitivity to increasing drought severity.

Our evaluation of water use efficiency (WUE) shows that each of the drought treatments resulted in higher WUE, expressed as tuber fresh weight produced per mm of water used, than the full-season100% irrigation treatment (Table 6). The most severe drought treatment (70 % ET early termination) produced the highest WUE for total yield. However, comparisons of WUE based on U.S. No. 1 yield show that treatments that included a reduction in late season water application had higher WUE than those that did not. The observation that WUE increases when potato plants experience drought has been reported by other investigators (Vos and Groenwold 1989a, b).

GemStar Russet and Ranger Russet had the highest WUE values for total yield, followed by Russet Burbank, Alturas, Russet Norkotah and Summit Russet. The range of WUE values in reported in this study is consistent with the results of numerous studies summarized by Wright and Stark (1990).

Table 6 Analysis of variance for treatment effects on water use efficiency (WUE) expressed as kg ha mm^{-1} water used, based on total yield and U.S. No. 1 yield

Source	*F*-value		
	DF	Total yield	US no. 1
Year	1	427.63 *** [a]	168.42 ***
Drought treatment	4	67.50 ***	15.43 ***
Year × drought treatment	4	9.96 ***	6.88 ***
Cultivar	5	71.02 ***	56.58 ***
Year × cultivar	5	7.34 ***	9.09 ***
Drought × cultivar	20	2.79 ***	2.79 ***
Year × drought × cultivar	20	1.09 ns	1.52 *
Drought treatment main effects		WUE total yield (kg ha mm^{-1})	WUE no. 1 yield (kg ha mm^{-1})
100 % ET full season		76.56 c [b]	54.72 c
100 % ET early termination		95.43 b	67.88 ab
70 % ET full season		94.53 b	63.56 b
70 % ET early termination		108.80 a	66.63 ab
100-70-50 gradual drought		98.09 b	70.98 a
LSD 0.05		3.95	4.41
Variety main effects		WUE total yield (kg ha mm^{-1})	WUE no. 1 yield (kg ha mm^{-1})
Alturas		91.85 c	62.16 cd
Gem Star Russet		107.57 a	85.75 a
Ranger Russet		106.92 a	69.64 b
Russet Burbank		100.91 b	46.88 e
Russet Norkotah		86.83 d	66.64 bc
Summit Russet		73.99 e	57.44 d
LSD 0.05		4.32	4.84

[a] *, *** indicate significance at $p=0.05$ and $p=0.001$, respectively; *ns* not significant

[b] Means in columns followed by the same letter are not significantly different at $p\leq0.05$

The WUE result for Russet Burbank is somewhat surprising, given its reputation as a drought sensitive cultivar (Miller and Martin 1987). However, that sensitivity is primarily related to its tendency to produce malformed tubers in response to drought. That tendency is expressed in the WUE results for U.S. No. 1 yield, which show that Russet Burbank had the lowest WUE value of all the cultivars. In contrast, GemStar Russet had the highest WUE for U.S. No. 1 yield, followed by Ranger Russet. Russet Norkotah and Alturas had intermediate WUE values, while Summit Russet again exhibited low WUE.

Differences in WUE among potato cultivars have been reported previously (Hill et al. 1985; Vos and Groenwold 1989a, b). Hill et al. (1985) reported that Russet Burbank showed a greater response to increasing water supply than either Kennebec or Lemhi Russet. They also observed that Russet Burbank's response to increasing water supply was more pronounced for U.S. No. 1 yield than total yield, which is consistent with the results of our study.

Vos and Groenwold (1989a) concluded that although WUE for six cultivars was inversely related to stomatal conductance, variation in photosynthetic characteristics among the cultivars also likely contributed to differences in WUE. Ierna and Mauromicale (2006) examined diffusive leaf resistance and photosynthetic rate in two moderately stressed potato cultivars, and found that the decrease in photosynthesis with increasing diffusive resistance was greater in the drought sensitive cultivar. Although measurements of stomatal conductance and photosynthesis were not collected in our study, the differences in WUE among cultivars suggest that their ability to fix carbon during periods of drought likely was key contributor to the differences in drought response.

Conclusions

For most of the cultivars evaluated in this study, providing full irrigation through mid-bulking, followed by a slow reduction in irrigation amounts was the best scenario for reducing yield losses when water supplies were deficient. Late maturing, stress-susceptible cultivars like Russet Burbank will likely be susceptible to large losses of marketable tubers under either moderate season-long stress, or sudden severe water stress caused by termination of irrigation. In contrast, an early maturing cultivar like Russet Norkotah can withstand a late season loss of water with little or no loss of yield as long as there is sufficient water during most of the tuber bulking period. More drought-tolerant cultivars like GemStar Russet or Ranger Russet can maintain relatively high yields of marketable tubers even under fairly severe stress during most of the tuber bulking period due to their higher yield potential. However, GemStar Russet and Ranger Russet were more sensitive to changes in drought severity than Russet Burbank, Russet Norkotah and Summit Russet.

Results from this study also show that cultivars within a similar maturity class can be affected differently by water stress. Alturas, for example, is a later maturing cultivar like Russet Burbank and Ranger Russet, but is even more sensitive to late season water shortages. This is likely due to a high late-season water requirement, which is related to its production of large, actively growing vines late in the growing season.

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