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Planting System Effect on Yield Response of Russet Norkotah to Irrigation and Nitrogen under High Intensity Sprinkler Irrigation

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Abstract Conversion of potato ridged-row planting systems to wide bed planting systems may increase water and nitrogen use efficiency in commercial irrigated potato production systems by reducing the amount of irrigation water and water applied nitrogen fertilizer bypassing the potato root zone. Wide bed planting systems consist of planting multiple rows on a wide bed with 20 to 35% higher plant population than found in conventional ridged-row planting systems. The objective of this study was to evaluate the effect planting system has on yield response of 'Russet Norkotah' potato to irrigation and nitrogen. Planting systems evaluated were (1) conventional ridged-row with dammer-diking; (2) 3.7 m wide bed with five potato rows spaced 66 cm between adjacent rows centered on the bed and; (3) 3.7 m wide bed with seven potato rows spaced 46 cm between adjacent rows. Six irrigation amounts, 50, 70, 85, 100, 115, and 130%, of estimated evapotranspiration after tuber initiation and four nitrogen rates, <20, 50, 100, and 150%, of conventional recommendations were applied to the three planting systems. Interactions between irrigation amounts and nitrogen rate were significant for total and U.S. No. 1 yield, irrigation water use efficiency, and gross return in one or both study years. Interactions between nitrogen rate and planting system were significant for total and U.S. No. 1 yield, irrigation water use efficiency and gross return in the first year of the study. Interactions between irrigation amount and planting system were not significant. In the first study year, total and U.S. No. 1 yields were significantly increased 12 and 19 percent, respectively, under the 7-row bed planting system compared to ridged-row planting system. Comparison of ridged-row planting system and 5-row bed planting system on 31 commercial potato fields in eastern Idaho representing a combined area of 2,800 ha over 5 years resulted in significantly higher total yield and irrigation water use efficiency with the bed planting system. The 5-row bed planting system averaged 6% higher total yield, 5% less water application and an 11% increase in irrigation water use efficiency. The results of this study demonstrate that under high intensity rate sprinkler irrigation in the soil and climatic conditions prevalent in eastern Idaho, bed planting systems provide viable production alternatives for irrigated potato production that may increase total yield, gross return, and irrigation water use efficiency.

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Resumen La conversión de los sistemas de plantación de papa de surco simple a cama ancha puede incrementar la eficiencia en el uso de agua y nitrógeno en sistemas de producción comercial de papa bajo riego, mediante la reducción de la cantidad de agua de riego y del fertilizante nitrogenado aplicado en el agua que penetra hasta la zona radical de la papa. Los sistemas de plantación de cama ancha consisten en plantar hileras múltiples en una cama amplia con una población de plantas de 20 a 35% mayor que los encontrados en los sistemas convencionales de surco simple. El objetivo de este estudio fue el de evaluar el efecto que el sistema de plantación tiene en la respuesta en el rendimiento de papa "Russet Norkotah" respecto al riego y al nitrógeno. Los sistemas de plantación fueron: (1) surco simple convencional con cortina de contención; (2) cama de

3.7 m de ancho con cinco hileras de papa espaciadas a 66 cm entre líneas adyacentes centradas en la cama, y (3) cama de 3.7 m de ancho con siete líneas de papa espaciadas a 46 cm entre líneas. A los tres sistemas de plantación se les aplicaron seis cantidades de riego, 50, 70, 85, 100, 115, y 130% de evapotranspiración después del inicio de la tuberización, y cuatro niveles de nitrógeno, <20, 50, 100, y 150% de las recomendaciones convencionales. Las interacciones entre las cantidades de riego y el nivel de nitrógeno fueron significativas para rendimiento total y U. S. No. 1, eficiencia de uso del agua de riego, y recuperación de la inversión en uno o en ambos años de estudio. Las interacciones entre el nivel de nitrógeno y el sistema de plantación fueron significativas para rendimiento total y U. S. No. 1, eficiencia en el uso del agua de riego, y recuperación de la inversión en el primer año del estudio. Las interacciones entre la cantidad de riego y el sistema de plantación no fueron significativas. En el primer año de estudio, los rendimientos totales y U.S. No. 1 aumentaron significativamente 12 y 19%, respectivamente, bajo el sistema de plantación de siete hileras por cama comparado con el del surco simple. La comparación del sistema de surco con el de la cama de cinco hileras en 31 campos comerciales de papa en el este de Idaho, que representa un área combinada de 2,800 ha, durante cuatro años, dio por resultado un mayor rendimiento total significativo y de uso eficiente del agua de riego con el sistema de plantación en camas. El sistema de cinco hileras por cama promedió 6% más de rendimiento total, 5% menos de aplicación de agua, y un aumento del 11% en la eficiencia del uso del agua de riego. Los resultados de este estudio demuestran que bajo un nivel de alta intensidad de riego por aspersión en el suelo y bajo las condiciones climatológicas prevalecientes en el este de Idaho, los sistemas de plantación en cama ofrecen alternativas viables de producción para la producción de papa bajo riego, que pudiera aumentar el rendimiento total, la recuperación de la inversión, y la eficiencia en el uso del agua de riego.

Keywords Irrigation · Sprinkler irrigation · Planting · Planting configuration · Bed planting · Irrigation water use efficiency

Introduction

Irrigated potato production in the arid western U.S. began in the late 1800's and early 1900's along with irrigation development. Surface irrigation, where water flows on the soil surface down slope between adjacent crop rows, was essentially the only form of irrigation for the first 50 years. The conventional ridged-row planting system used in rain-fed production areas provided a convenient furrow between potato rows for surface irrigation. Over the past 60 years, advances in irrigation technology and irrigated potato production practices have substantially changed. Yet, the ridged-row planting system for commercial irrigated potato production largely remains unchanged. Currently, irrigated potato production in the Pacific Northwest, which produces over 50% of the U.S. fall potato production, is essentially all sprinkler irrigated with center pivot irrigation systems being the predominate type of irrigation system. The traditional ridged-row planting system may no longer be necessary for irrigation water distribution and could be actually antagonistic to efficient water management under high intensity (center pivot) sprinkler irrigation. Runoff from the sides of a ridged potato row leads to water ponding in the furrow and water infiltration below and to the side of a substantial percentage of the potato root zone (Saffigna et al. 1976) resulting in sub-optimal water application efficiency and nitrogen (N) leaching. Saffigna et al. (1977) conducted a potato N balance using lysimeters under solid set sprinkler irrigation and found that 42% of total N (120 kg N/ha) was leached below the crop root zone when irrigation was scheduled to match crop evapotranspiration. Waddell et al. (2000) reported similar N losses under sprinkler irrigated potatoes when irrigation was scheduled to match crop evapotranspiration. These results demonstrate that 20 years of potato production research has not substantially reduced N leaching from sprinkler irrigated potato production. Runoff of sprinkler applied irrigation water from ridged-rows can result in a dry zone near the center of the potato row (Robinson 1999). Cooley et al. (2007) measured soil water distribution in ridged-row planted potatoes under sprinkler and drip irrigation where the greatest densities of roots occurred. They found that soil water content averaged 0.03 m^3m^{-3} (>60% of readily available water) greater under drip irrigation compared to sprinkler irrigation. Decreased water content in the root zone center of the ridged-row planted potatoes under sprinkler irrigation became more prominent as the growing season progressed, resulting in hydrophobic soil conditions midway through the growing season. The development of a dry zone in the potato root zone can lead to over-irrigation as producers try to move water into the dry zone, which then exacerbates N leaching. An alternative to the conventional ridged-row planting system is desired to increase water and N use efficiency in sprinkler-irrigated potato production.

Planting potatoes without ridged-rows or in beds of varying widths has been studied on a limited basis with mixed results. Nelson (1967) compared planting in 96.5 cm wide beds with three rows spaced 48.2 cm apart and conventional ridged-row planting for five potato varieties in non-irrigated production. Results did not show an advantage for the bed system over conventional ridged-row planting. Higher plant populations generally resulted in slightly higher yields and a greater number of small tubers. Wayman (1969) investigated planting potatoes in beds 152 cm and 172 cm wide with four equally spaced rows. He abandoned the use of four row beds after the first year due to potato harvester draft requirement being too large for available equipment. He continued to study semi-bed configurations with two potato rows per semi-bed spaced 76 cm apart. He concluded that mechanized harvest was possible but when compared to conventional ridged-row planting, the slight yield increase might not compensate for higher seed rates and increased harvest difficulties. Thompson et al. (1974) investigated flat bed and conventional ridged-row planting with various plant arrangements and populations for canning potatoes. Flat beds 1.5 m wide were compared with ridged-row planted potatoes spaced 60 and 90 cm apart with two crop rows per ridge. They concluded that using ridged-row planting 90 cm apart with two crop rows per ridge provided the most consistent yield and had certain cultural advantages. Prestt and Carr (1984) summarized research results of bed versus ridged-row planting system for potatoes. They found that the advantages of bed planting systems included more uniform water distribution in the potato root zone, significantly less rainfall runoff, faster emergence and significantly greater yield. McKeown (1987) investigated bed planting using 1.5 m wide beds for seed potato production of Yukon Gold potatoes. One to three rows were planted on the beds at equal spacing between rows that were ridged as they developed. Based on yield data and net return estimates, the triple row planted bed resulted it the highest net return. Fisher et al. (1993) evaluated yield response of ridged-row planting and two rows per bed under irrigated and non-irrigated conditions. They found a significant increase in yield associated with the use of beds in several experiments. They concluded that increased water use efficiency was partially responsible for the yield increase. They also noted that the yield advantage was reduced or eliminated under irrigated conditions. Dickson et al. (1992) investigated planting three rows of potatoes on 2.8 m wide beds as a means of reducing the effect of compaction on potato production. They found that planting in a bed increased total and marketable potato yields 14% and 18%, respectively. The conventional ridged-row planting system produced 30% more clods at harvest compared to the bed planting system. Mundy et al. (1999) evaluated potato production in ridges versus 1.9 m wide flat beds with three rows per bed under irrigated and non-irrigated conditions. They found that beds had higher soil water contents early in the season, reduced daily soil temperature fluctuations, and similar yields compared to ridged-row planted potatoes. They concluded that since bed planting did not significantly increase yield, it was not an economically advantageous commercial production practice. However, they did note that if equipment was commercially available and the inputs of seed, water, and fertilizers were optimized, bed planting may be economically advantageous. Alva et al. (2002) evaluated yields from conventional ridged-row planted, semi ridged-row planted and flat-planted potatoes under high application rate sprinkler irrigation as a means to reduce runoff, erosion and leaching of agrochemicals. They found that potato yield and quality under semi ridged-row planting and flat planting was not significantly different from conventional ridged-row planting in 2 of 3 years. They concluded that semi ridged-row and flat planting under the soil and climate conditions of the Pacific Northwest is a viable potato production practice to reduce runoff, erosion and nutrient losses. A review of available literature reveals that planting potatoes in beds has been considered for various reasons. The success of field studies have been mixed, but planting in beds has rarely reduced potato yield or quality. Planting in beds has generally increased soil water content in the root zone and in some cases has increased water use efficiency. Plant population appears to be a key element for bed planting systems due to the opportunity to greatly increase plant density. Previous studies on bed planting systems have employed a wide range of plant populations relative to conventional ridged-row planting. Plant populations for bed planting systems have ranged from 30% to 300% greater than comparison conventional ridged-row planting. Planting potatoes in beds provides a greater opportunity to manipulate plant population compared to ridged-row planting to target a specific tuber size market.

The potential benefits from bed planting systems rather than ridged-row planting systems has lead to the development of two wide bed potato bed planting systems being tested in Idaho by Western Ag Research (Blackfoot, ID). The bed planting systems are both 3.7 m wide with either: 1) 5 rows spaced 66 cm apart centered on the bed, or 2) 7 rows equally spaced 46 cm apart. The 3.7 m bed width was selected to be compatible with existing 4-row (0.91 m row spacing) conventional ridged-row potato harvesting equipment. Potato planters for both wide bed planting systems are currently commercially available from Harriston Industries (Minto, ND) and Spudnik Equipment Company (Blackfoot, ID). Some producers have reported increased yields and reduced irrigation requirements from bed planting systems.

This study was designed based on practices reported by producers evaluating potato bed planting systems in eastern Idaho. The study was designed as a system study to compare conventional ridged-row planting with bed planting systems being evaluated in eastern Idaho. Differences in comparing the planting systems included planting configuration and plant populations. Plant populations for the bed planting systems were 25% to 34% higher than for the conventional ridged-row planting system. The objectives of this study were 1) evaluate the effect of planting system has on yield response of Russet Norkotah potato under different levels of irrigation and nitrogen on replicated plots and 2) document total yield and water use of bed planting systems on commercial fields.

Methods and Materials

Site Description

A 2-year field study was conducted during 2006 and 2007 at the USDA Agricultural Research Service Northwest Irrigation and Soil Research Laboratory in Kimberly, ID under lateral-move sprinkler irrigation. Soil at the site was a Portneuf silt loam (coarse-silty, mixed, mesic Durixerollic Calciorthids; sand 14%, clay 17%, silt 69%). The soil profile was well drained with a saturated hydraulic conductivity of 3.2 cm/h. Available water holding capacity was 0.2 cm cm^{-1} (USDA 2009a). Commercial fields used in the study were located in eastern Idaho along the Snake River Plain from American Falls to Ashton, Idaho. The soils were well drained with textures ranging from loam to loamy sand.

Experimental Design

The Kimberly field plot study was arranged in a strip split plot statistical design, Fig. 1. Treatments consisted of three planting systems (conventional ridged-row, 5-row bed and 7-row bed), four nitrogen rates (<20, 50, 100 and 150% of recommended N rate) and six irrigation amounts (50, 70, 85, 100, 115, 130% of estimated evapotranspiration (ET)). Each of the three planting system treatments was a strip plot 250 m in length. Three adjacent parallel strips, one for each planting system treatment, were treated as a randomized block. Each randomized block of planting system strips was bordered along both lengths by a strip of the conventional ridged-row planting. Two adjacent randomized blocks of planting system strips were treated as an irrigation block (blocks 1 and 2 and blocks 2 and 3, Fig. 1). An irrigation block consisted of six parallel irrigation strips orientated perpendicular to two randomized blocks of planting system strips with the six irrigation treatments randomly assigned along the length of the planting system strips. Irrigation was applied using a linear-move irrigation system which traveled perpendicular to the planting system strips. Only two irrigation blocks were used in the study with different randomization of the irrigation treatments. The irrigation blocks were separated by a 33 m wide strip of barley. Each planting system strip—irrigation strip treatment combination was split into four nitrogen treatment plots measuring 6 m in length and 3.7 m wide near the center of each irrigation treatment strip. Centering the four nitrogen treatments allowed for 8.6 m borders at each end of the nitrogen treatment plots to guard against reduced water application uniformity caused by towers

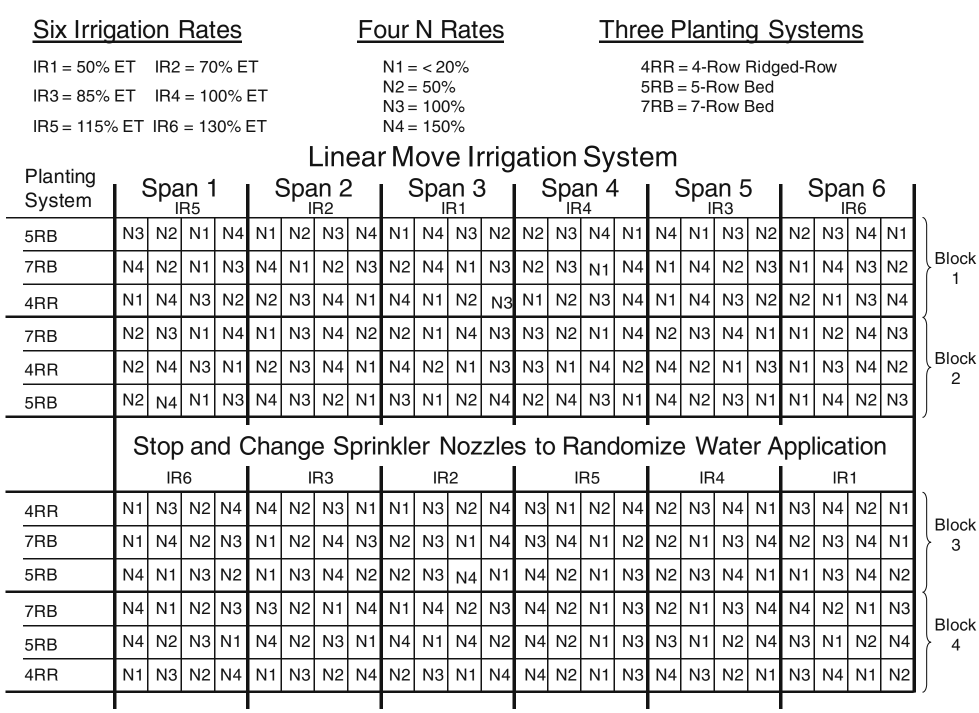

Fig. 1 Experiment design field layout under six span linear move irrigation system. Treatments were six irrigation rates relative to 100% estimated daily ET after tuber initiation, four seasonal N application rates relative to standard recommendations and three planting systems

on the linear-move irrigation system. The same experimental design was used both years. The second year study plots were located 34 m north of the first years study plots.

Thirty-one commercial potato fields in eastern Idaho where the 5-row bed system was used were selected for comparison of total yield and water application with 31 conventional ridged-row planted fields over a 5-year period, 2005–2009. The 31 5-row bed planting field sites were selected based on the criteria that the conventional ridged-row planted field used for comparison was managed by the same producer, located within 2 km of the bed-planted field site, planted to the same potato cultivar and have similar planting and vine killing dates.

Crop Production Practices

The Russet Norkotah cultivar (*Solanum tuberosum*) was selected for the Kimberly field plots because it has a smaller plant size and shallower root zone than other potato varieties (Bohl and Love 2003). These characteristics suggest that Russet Norkotah may respond well to a higher plant population in a bed planting system. Also, Russet Norkotah is a common cultivar grown in Idaho, consisting of 14.6% of the total production in 2009 (USDA 2009b).

Irrigation and nitrogen rates were uniform throughout the tuber initiation growth stage to ensure healthy plant establishment. Total seasonal N rates of <20, 50, 100 and 150% of the University of Idaho recommendations (Bohl and Love 2003) for Russet Norkotah potatoes with a yield goal of 56 Mg ha^{-1} were applied each year. A zero seasonal fertilizer N rate was not used because a local source of dry phosphate fertilizer without N was unavailable. Total seasonal N application rates of 50, 100 and 150 of recommended were obtained by hand applying Urea fertilizer at different rates following tuber initiation. Urea application was immediately followed by 15 mm of irrigation to all plots to ensure equal incorporation and limit ammonia volatilization losses. In 2006, 19 kg N, 90 kg P_2O_5 and 112 kg K_20 ha^{-1} were broadcast preplant and incorporated with a disk harrow. The previous crop was forage corn. Urea was hand applied on 14 June at 0, 93, 205 and 317 kg N ha^{-1} to give total N applications of 19, 112, 224, 336 kg N ha^{-1} (<20, 50, 100 and 150% of recommended) In 2007, 63 kg N, 298 kg P_2O_5 and 152 kg K_20 ha^{-1} were broadcast preplant and incorporated with a disk harrow. The previous crop in 2007 was spring barley with no straw removal. Urea was hand applied on 12 June at 0, 97, 257 and 417 kg N ha^{-1} to give total N applications of 63, 160, 320, 480 kg N ha^{-1} (<20, 50, 100 and 150% of recommended).

Irrigation rates of 50, 70, 85, 100, 115 and 130% of estimated evapotranspiration were imposed following N rate applications and remained the same until vine kill. Evapotranspiration estimates were those published by the U.S. Bureau of Reclamation AgriMet System (http://www.usbr.gov/pn/agrimet/) based on climatic conditions measured within 4 km of the study site. Irrigation management was monitored using tensiometers placed at a depth of 20 cm in the crop row in multiple 100% irrigation plots to ensure soil moisture tension remained below 60 kPa prior to irrigation.

Irrigation occurred twice a week early and late in the growing season and three times a week during the peak of the growing season. In 2006, differential irrigation rates started on 16 June and continued through 5 September. In 2007, differential irrigation rates started on 15 June and continued through 24 August. In 2007, tensiometer values prior to irrigation were used to adjust calculated irrigation requirements based on AgriMet ET estimates. On the day of scheduled irrigation and prior to irrigation, if the average tensiometer reading was below 40 kPa, the irrigation amount based on ET was reduced 20%. If the average tensiometer readings was above 40 kPa, no adjustment was made to the irrigation amount. This process was repeatedly followed throughout the growing season.

Commercial planters were used to plant the Kimberly field plots. Plot size was 6 m in length by 3.7 m wide. Conventional ridged-row planting consisted of four rows spaced 91 cm between rows. The conventional ridged-row plots were ridged and dammer diked (reservoir tillage) immediately following planting and prior to pre-emergence herbicide application. Actual plant density was estimated by counting plants in ten randomly selected plots for each planting system. Target plant populations were 38,800 plants ha^{-1} for the 5-row bed, 41,700 plants ha^{-1} for the 7-row bed, and 31,100 plants ha^{-1} for conventional ridged-row planting. In 2006, the 7-row bed and conventional ridged-row plots were planted 5 May and the 5-row bed plots were planted on 11 May. In 2007, the 5-row bed plots were planted on 17 April and the 7-row bed and conventional ridged-row plots were planted 19 April. Herbicides were applied pre-emergence uniformly to all plots in 2006 and 2007. Prior to harvest, potato vines were killed with a desiccant spray on 12 and 7 September in 2006 and 2007, respectively.

Data Collection and Analysis

Tuber samples from the plot study were harvested with a conventional 4-row potato windrower on 25 and 24 September in 2006 and 2007, respectively. An area 4.9 m long by 3.7 m wide was harvested from each plot, bagged by hand and stored until graded. Plot samples were visually graded and passed through an automated potato sizing machine that weighed and recorded the weight of each tuber on 16 and 15 October in 2006 and 2007, respectively.

Irrigation water use efficiency was calculated as total yield divided by the depth of irrigation plus precipitation applied to the field. Gross receipts were calculated by multiplying the eastern Idaho shipping point price quoted by tuber grade and size class by measured plot yields per hectare in each corresponding tuber grade and size class and summing over the tuber grade and size classes from each plot. Gross return was calculated by subtracting a fresh pack processing fee of \$114.32 Mg^{-1} from gross receipts. Eastern Idaho shipping point prices used for 2006 and 2007 crops are listed in Table 1 and equivalent to those reported by USDA (http://www.marketnews.usda.gov) for 11 January 2007 and 12 January 2008, respectively.

Water application to 62 commercial fields was measured using a minimum of four rain gauges at one or more locations in each field. The rain gauges were of a design that had a small diameter opening to the atmosphere to minimize water evaporation from the water storage chamber. The rain gauges were manually read and emptied three times a week during the growing season. The rain gauge readings were averaged to determine water application and totaled for the season. Producer irrigation records for hours of irrigation were used as a data quality check of the rain gauge readings on a weekly basis.

Field average total yield for the 62 commercial potato fields was determined using two methods which were averaged to obtain yield. Method one was a count of the number of truck loads harvested from the field area. The harvested mass in each truck was estimated based on the volume of each truck and the density of potato tubers. Truck mass was adjusted for dirt tare based on data comparing truck load mass delivered to processing plant with process mass delivered as determined by the potato processor. The second method was based on measured volume of the potato tubers in storage harvested from the field area and the density of potato tubers. The density of potato tubers was taken as 773 kg m^{-3}.

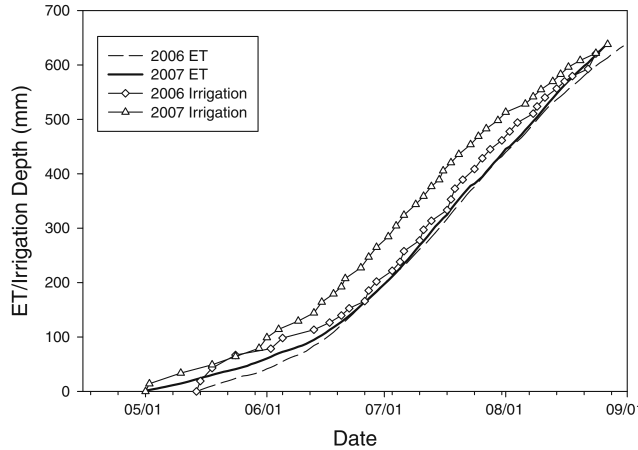

Fig. 2 Cumulative seasonal estimated ET and irrigation application depths for the 100% ET treatment in 2006 and 2007

Statistical Analysis

Analysis of variance was conducted on the Kimberly plot study data using the PROC MIXED procedure in SAS (SAS Institute Inc, Cary, NC) to test the main effects of planting system, irrigation level, N application rate and interactions on yield, irrigation water use efficiency and

Table 1 USDA reported Eastern Idaho shipping point potato prices used in computing gross receipts for 2006 and 2007 crops

Tuber Size Class grams	Price (\$/Mg)	
	2006	2007
U.S. No. 1		
<113	\$ 88.13	\$ 88.13
113–<213	\$ 264.38	\$ 385.55
213–<240	\$ 352.50	\$ 418.59
240–<268	\$ 352.50	\$ 451.64
268–<304	\$ 352.50	\$ 451.64
304–<351	\$ 352.50	\$ 451.64
351–<461	\$ 352.50	\$ 451.64
461–<510	\$ 352.50	\$ 451.64
510–624	\$ 352.50	\$ 451.64
>624	\$ 88.13	\$ 88.13
U.S. No. 2		
<170	\$ 88.13	\$ 88.13
170–<283	\$ 187.27	\$ 154.22
>283	\$ 231.33	\$ 220.31

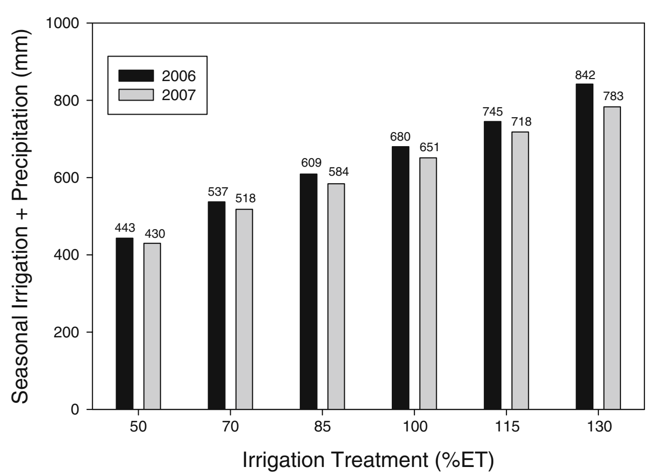

Fig. 3 Cumulative seasonal irrigation and precipitation application for each of the six irrigation treatments in 2006 and 2007

Table 2 Measured plant populations for each planting system in both years along with target plant populations

Planting System	Plant Population (plants ha^{-1})		
	Target	2006	2007
Ridged-Row	31,100	31,201	31,717
5—Row Bed	38,800	38,779	43,570
7—Row Bed	41,700	41,738	38,248

gross return. Sample SAS code used for the statistical analysis is included in the Appendix for reference. Error terms used for testing significance of main effects and interactions were determined by the Proc Mixed procedure based on the random effects identified in the random statement of the Proc Mixed procedure (Appendix). The Proc Mixed procedure used the appropriate linear combinations of the variance component estimates as denominators for the F-tests for the fixed effects. The actual combinations that are used depend on whether or not some of them are estimated to be zero. Differences between treatment means were evaluated by calculating treatment least square mean differences and comparing the means based on the overlap of the mean confidence intervals. The probability level for the degree of overlap was evaluated using a *t*-test. The level of significance for mean comparison t-tests was determined using a Bonferroni adjusted *p*-value to limit the overall experimental *p* value to 0.05.

Statistical analysis of total yield, irrigation water use and irrigation water use efficiency comparisons between the 5-row bed system and ridged-row planting system in commercial fields was performed using a paired *t*-test with $p=0.05$.

Results and Discussion

Seasonal Irrigation Amounts

Estimated cumulative ET for potato from the U.S. Bureau of Reclamation AgriMet system (http://www.usbr.gov/pn/agrimet/) was 635 and 640 mm in 2006 and 2007, respectively (Fig. 2). Seasonal irrigation water application for the 100% ET treatments were 620 and 638 mm for 2006 and 2007, respectively (Fig. 2). Growing season precipitation was 61 and 12 mm for 2006 and 2007, respectively. In 2006, seasonal water application ranged from 443 to 842 mm or 65% to 124% of the 100% ET treatment (Fig. 3). In 2007, seasonal water application ranged from 430 to 783 mm or 66% to 120% of the 100% ET treatment (Fig. 3).

Plant Populations

In 2006, the measured plant populations were very close to the target population for each planting system field plot (Table 2). However, in 2007 the measured plant population for the 5-row bed system was 12% above the target plant population (Table 2). A review of the calibration chart for the 5-row bed planter electronic controller revealed that the operator used the incorrect column from the chart and consequently set the electronic controller incorrectly. In 2007 the measured plant population for the 7-row bed system was 8 percent below the target population (Table 2). A clear reason for this result, other than planter variability, is unknown.

Field studies investigating the effect of plant population on potato yield have been conducted in North America under both irrigated (Iritani et al. 1972; Lynch and Rowberry 1977; Davis and Groskopp 1979; Rykbost and

Table 3 Analysis of variance summary for total and U.S. No. 1 tuber yields, irrigation water use efficiency and gross return as influenced by irrigation, planting system, and nitrogen. *p*-values in bold are significant at the 0.05 probability level

Source	DF	Total Tuber Yield (Mg ha^{-1})		No. 1 Tuber Yield (Mg ha^{-1})		Irrigation Water Use Efficiency (Mg ha^{-1} mm^{-1})		Gross Return ($ ha^{-1})	
		2006 *p*-value	2007	2006	2007	2006	2007	2006	2007
Irrigation (I)	5	**0.0008**	**0.0001**	**0.0129**	**0.0001**	**0.0032**	0.0727	**0.0046**	**<0.0001**
Planting System (PS)	2	**0.0157**	0.2124	**0.0019**	0.0991	**0.0153**	0.2389	**0.0041**	0.6957
Nitrogen (N)	3	**0.0001**	**0.0061**	**0.0001**	**0.0136**	**<0.0001**	**0.0089**	**<0.0001**	**0.0004**
I × PS	10	0.1921	0.7942	0.3128	0.7714	0.0545	0.7840	0.3676	0.9343
I × N	15	**0.0070**	**0.0008**	0.1047	**0.0031**	0.2088	**0.0016**	**0.0285**	**0.0034**
N × PS	6	**0.0061**	0.1004	**0.0233**	0.0750	**0.0132**	0.1205	**0.0083**	0.0571
I × N × PS	30	0.9681	0.1181	0.5891	0.2067	0.9847	0.1135	0.7416	0.3865

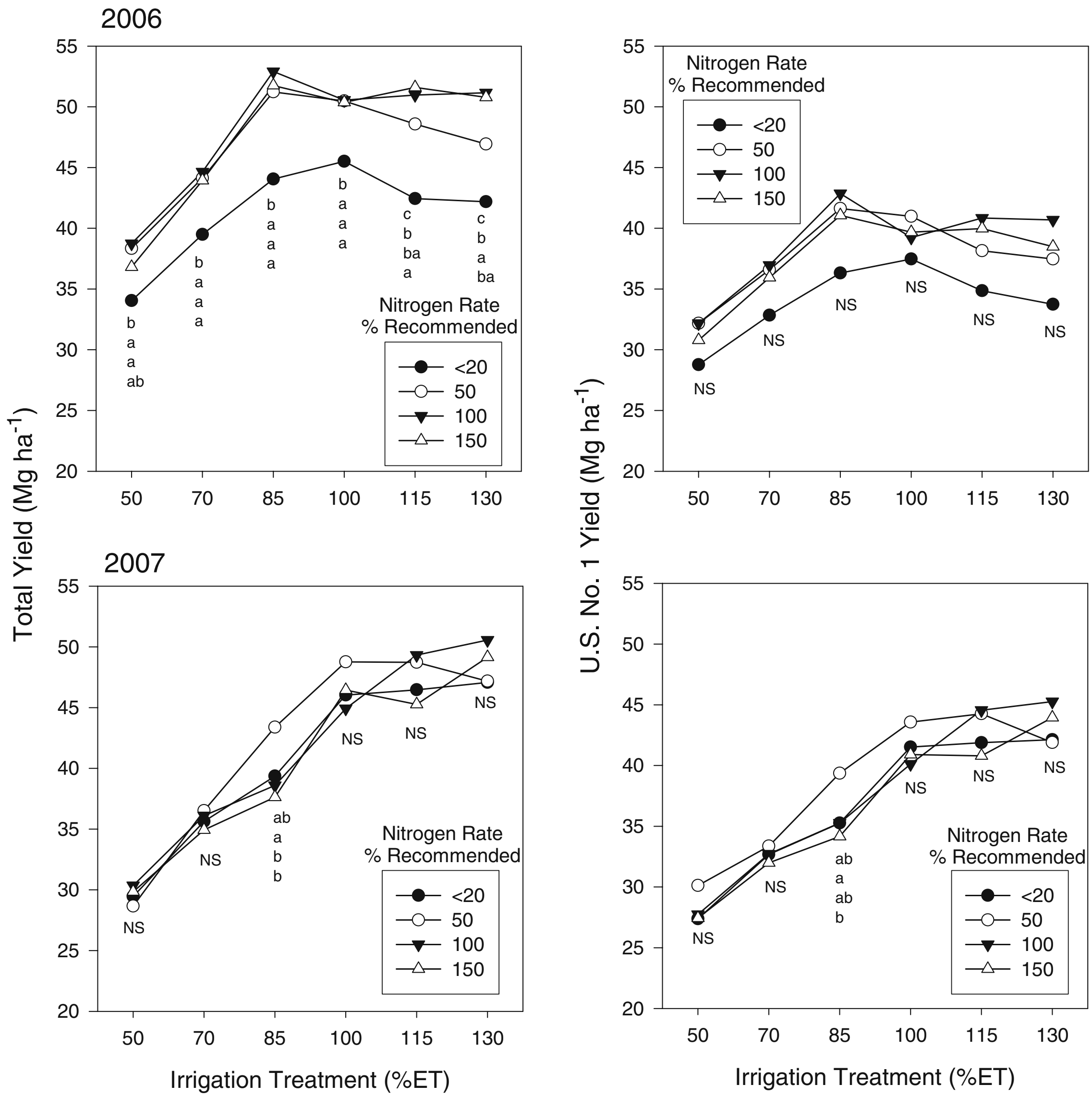

Fig. 4 Total and U.S. No. 1 yield as influenced by interaction between irrigation treatment and nitrogen rate for 2006 and 2007. Data averaged over three planting systems in each year. For each irrigation treatment, nitrogen treatments with the same letter are not significantly different at the 0.05 probability level based on least square mean confidence intervals. Treatment differences represented by letters from top to bottom correspond to treatments in legend from top to bottom. NS = not significant at the 0.05 probability level

Maxwell 1993; Love and Thompson-Johns 1999) and non-irrigated (Entz and LaCroix 1984; Rex (1990); Nelson 1967; White and Sanderson 1983; Rex et al. 1987; Rex 1991) conditions. None of these studies found a significant difference in total or U.S. No. 1 yields for changes in plant population of less than 21%. Of particular interest here is the study of Rykbost and Maxwell (1993) conducted in the Klamath Basin of Oregon with Russet Norkotah, which found no significant difference in total or U.S. No. 1 yields for a plant population range of 41,152 to 72,621 plants ha^{-1}. Although plant populations for the 5- and 7-row bed systems at the Kimberly field study varied between years by 8% and 12%, respectively, published studies found no significant difference in total or U.S. No. 1 yields for this level of difference in plant populations. Based on the above cited literature, plant populations for the 5- and 7-row beds were considered equivalent across years.

Total and U.S. No. 1 Yield

The interaction between irrigation and N treatments (I × N Table 3) was significant for total yield in 2006 and for total and U.S. No. 1 yields in 2007. In 2006, total yield was significantly lower for the <20% of recommended N treatment where zero N was applied following tuber initiation for irrigation rates greater than 50% ET (Fig. 4). In 2006, there was no significant difference in total yield between N applications applied after tuber initiation (50, 100 and 150% of recommended N) for the 50% to 100% ET irrigation treatments. For the 115% and 130% ET irrigation rates, the <20% recommended N rate treatment had lowest total yield. In 2007, significant differences in total and U.S. No. 1 yields between N treatments were found for the 85% ET irrigation rate only. Total yield for the 50% of recommended N rate was significantly greater than for the 100 and 150% of recommended N rates and U. S. No. 1 yield for the 50% of recommended N rate was significantly greater than for the 150% of recommended N rate. The 50% of recommended N rate appears to have been the optimum rate for maximizing total and U.S. No. 1 yields as it resulted in the numerically largest yields for irrigation treatments ranging from 70% to 100% ET. Nitrogen treatments in excess of 50% of recommended N may have promoted vegetative growth rather than tuber growth over this range in irrigation treatments while the <20% of recommended N treatment was insufficient for maximum tuber growth over the range in irrigation treatments. In general, total yield increased with seasonal water application to a maximum and then decreased or remained relatively constant as seasonal water application amount continued to increase. For low N rates, irrigation in excess of crop ET caused leaching of N below the potato root zone and decreased yield. For high N rates, irrigation in excess of crop ET did not decrease yield. High N rates mitigated the nitrogen leaching effect on total yield. Stark et al. (1993) found that excess irrigation reduced root zone and petiole NO_3–N concentrations during substantial portions of the tuber bulking period. However, they did not find a significant interaction between irrigation and N treatments. This is likely due to multiple applications of N fertilizer with the irrigation water during the tuber bulking period. The addition of N fertilizer during the tuber bulking period reduced N leaching by limiting the amount of N stored in the soil profile available to leaching, thereby reducing the effect of N leaching on yield. In the Kimberly field study, N fertilization was applied once following tuber initiation and available for leaching throughout the tuber bulking period. The significant interaction between irrigation and N rates found in this study supports the management practice of applying a substantial portion of the N fertilizer requirement in multiple applications during the tuber bulking period to minimize N leaching and maximize yield.

In 2006, total and U.S. No. 1 yields averaged over the three planting systems was maximized by the 85% irrigation treatment (Fig. 4) for the 50, 100 and 150% of recommended N application rates indicating that the 100% ET irrigation treatment was likely excess irrigation. For this reason tensiometers were used as the primary irrigation scheduling tool in 2007 rather than estimated ET alone. In 2007, total and U.S. No. 1 yields for all N treatments were relatively constant at irrigation levels of 100% ET and above (Fig. 4) indicating that irrigation scheduling using tensiometers to adjust irrigation amounts based on ET estimates was effective.

The interaction between planting system and N treatment (N × PS Table 3) was significant for both total and U.S. No. 1 yields in 2006 and not significant in 2007. This significant interaction indicates that there were fertilizer N

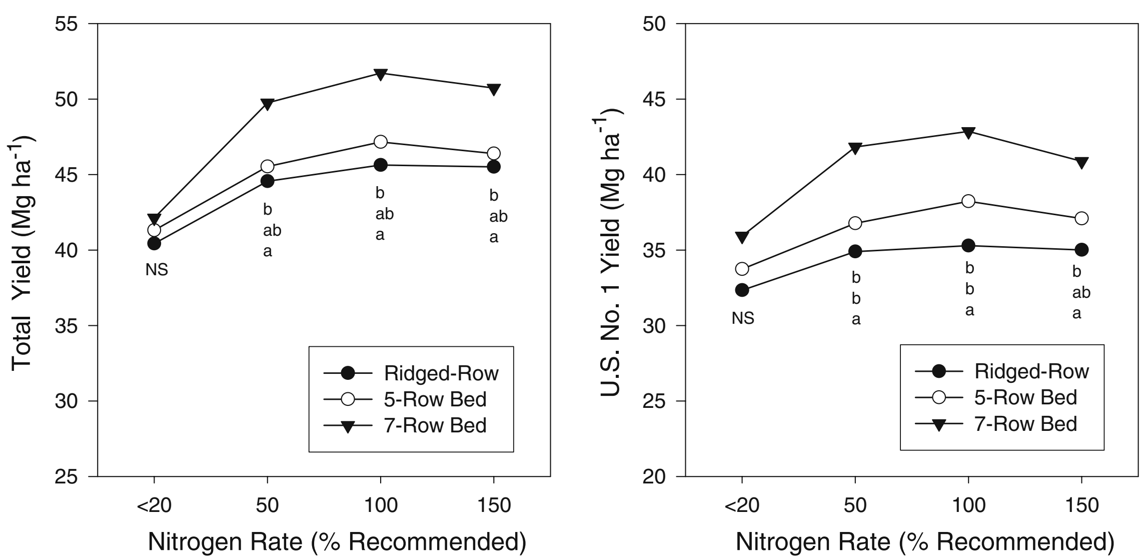

Fig. 5 Total and U.S. No. 1 yield as influenced by nitrogen application rate for 2006. Data averaged over six irrigation treatments in each year. For each nitrogen rate, planting system treatments with the same letter are not significantly different at the 0.05 probability level based on least square mean confidence intervals. Treatment differences represented by letters from top to bottom correspond to treatments in legend from top to bottom, Ridged-Row—5-Row Bed—7-Row Bed, respectively. NS = not significant at the 0.05 probability level

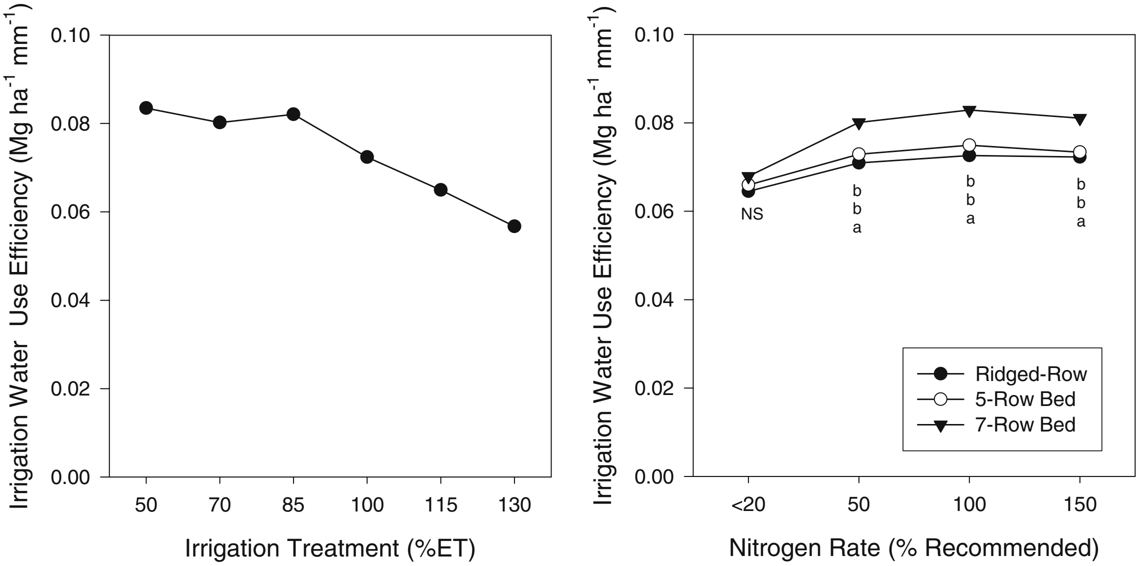

Fig. 6 Irrigation water use efficiency as influenced by irrigation treatment and interaction between nitrogen rate and planting system for 2006. Data averaged over planting system and nitrogen rate for irrigation treatment effect. Data averaged over the six irrigation treatments for the interaction of nitrogen and planting system. For each nitrogen rate, planting systems with the same letter are not significantly different at the 0.05 probability level based on least square mean confidence intervals. Treatment differences represented by letters from top to bottom correspond to treatments in legend from top to bottom, Ridged-Row—5-Row Bed—7-Row Bed, respectively. NS = not significant at the 0.05 probability level

use efficiency differences among planting systems in 2006. In 2006, total and U.S. No. 1 yields of the 7-row bed system were significantly greater than for the ridged-row system for the 50, 100 and 150% of recommended N application rates (Fig. 5). Total and U.S. No. 1 yields were significantly increased 12 and 19%, respectively, with the 7-row bed system compared to the conventional ridged-row system. Growing season conditions that reduced yield and quality regionally may have reduced the potential yield differences between bed planting systems and conventional ridged-row planting in 2007. The improved yield response to fertilizer N associated with the 7-row bed system in 2006 may be the result of reduced N leaching and more effective extraction of N fertilizer from the potato root zone. The 7-row bed system may have reduced N leaching by reducing ponding of water in the furrow which infiltrates beyond the extent of much of the potato root zone in ridged-row systems. The 7-row bed system is potentially less limiting than the ridged-row system to horizontal expansion of the plant root system by elimination of the furrow between ridged potato rows and a greater in-row distance between adjacent plants which could increase the effective volume of soil for root extraction of N fertilizer by each plant.

Irrigation Water Use Efficiency

In 2006, irrigation water use efficiency was relatively constant for irrigation treatments of 85% ET and less (Fig. 6). Irrigation water use efficiency decreased linearly

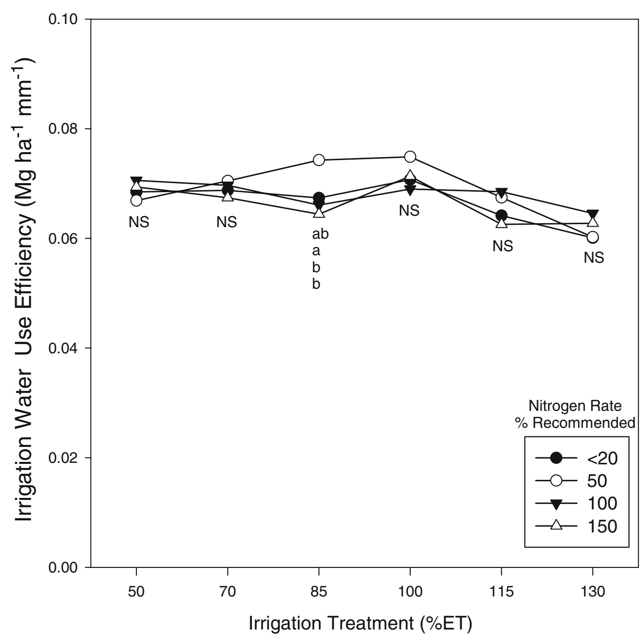

Fig. 7 Irrigation water use as influenced by interaction between irrigation treatment and nitrogen application rate 2007. Data averaged over three planting systems. For each irrigation treatment, nitrogen treatments with the same letter are not significantly different at the 0.05 probability level based on least square mean confidence intervals. Treatment differences represented by letters from top to bottom correspond to treatments in legend from top to bottom. NS = not significant at the 0.05 probability level

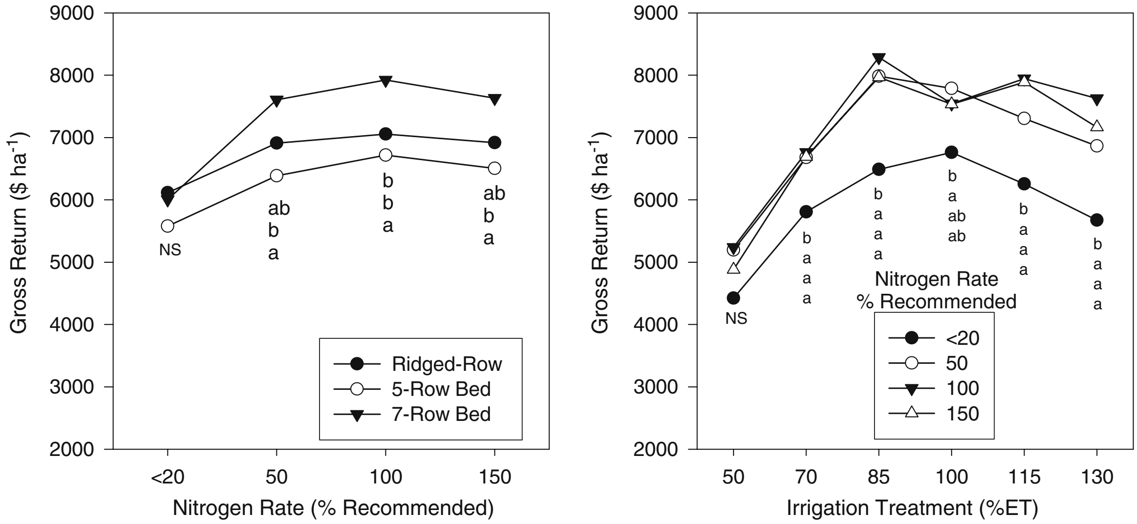

Fig. 8 Gross return as influenced by interaction between nitrogen rate and planting system and nitrogen rate and irrigation treatment for 2006. Data averaged over irrigation treatments for nitrogen rate and planting system interaction and three planting systems for interaction between irrigation and nitrogen treatments. For each nitrogen or irrigation treatment, treatments with the same letter are not significantly different at the 0.05 probability level based on least square mean confidence intervals. Treatment differences represented by letters from top to bottom correspond to treatments in legend from top to bottom. NS = not significant at the 0.05 probability level

with irrigation treatments of 85% ET and greater. For irrigation treatments of 85% ET and less, essentially all applied water was consumed by the potato plants. Total yield increased linearly (Fig. 4) in proportion to applied water over the range of 50% to 85% ET, resulting in a near constant value of irrigation water use efficiency. For irrigation treatments greater than 85% ET, some of the applied water is not used by the potato plants for tuber production. Increasing irrigation amounts led to greater amounts of water not consumed by the potato plants and likely to drainage from the plant root zone. The steady decline in irrigation water use efficiency with irrigation treatments greater than 85% ET was a result of decreasing yield (Fig. 4) likely due in part to N leaching. The decrease in water use efficiency above 85% ET indicates that the 100% ET treatment was likely excess irrigation.

In 2006, the interaction between nitrogen treatments and planting systems was significant for irrigation water use efficiency (N × PS, Table 3). Water use efficiency was significantly greater for the 7-row bed system for all N application treatments after tuber initiation (50, 100 and 150% of recommended N) (Fig. 6). This result is due to the interaction of N treatment and planting system for total yield (Fig. 5) since irrigation water use efficiency is directly proportional to total yield.

In 2007, the interaction between irrigation and N treatments was significant (I × N, Table 3). There was a significant difference in irrigation water use efficiency between N treatments for the 85% ET irrigation treatment only (Fig. 7). Irrigation water use efficiency for the 50% of recommended N treatment was significantly greater than the 100% and 150% of recommended N treatments. This significant interaction is the result of the significant interaction for total yield with the same treatment combinations (Fig. 4). Irrigation water use efficiency averaged over the N treatments remained fairly constant for irrigation treatments of 100% ET and less, then steadily decreased for irrigation treatments greater than 100% ET.

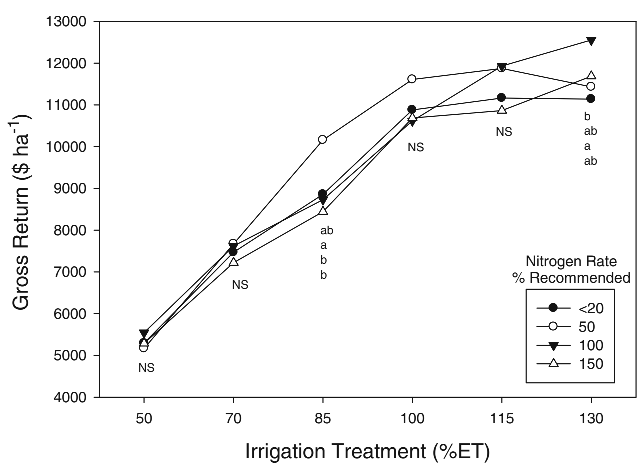

Fig. 9 Gross return as influenced by interaction between irrigation and nitrogen treatments for 2007. Data averaged over three planting systems. For each irrigation treatment, nitrogen treatments with the same letter are not significantly different at the 0.05 probability level based on least square mean confidence intervals. Treatment differences represented by letters from top to bottom correspond to treatments in legend from top to bottom. NS = not significant at the 0.05 probability level

Table 4 Comparison of yield, applied water, and irrigation water use efficiency (IWUE) of 5-row bed system and ridged-row planted potatoes of various varieties on commercial fields in southeastern Idaho for 2005 through 2009

Site No.	Cultivar	Beds			Ridged-row Planted			Combined
		Yield (Mg ha^{-1})	Water (mm)	IWUE (Mg ha^{-1} mm^{-1})	Yield (Mg ha^{-1})	Water (mm)	IWUE (Mg ha^{-1} mm^{-1})	Area (ha)
1	Russet Norkotah TXNS112[a]	53.1	490	0.108	46.9	470	0.100	49
2	Russet Norkotah TXNS112	55.0	335	0.164	53.7	345	0.155	77
3	Sierra Gold	50.7	470	0.108	37.6	485	0.077	83
4	Russet Norkotah TXNS112	45.3	546	0.083	34.0	531	0.064	128
5	Russet Norkotah TXNS112	51.6	681	0.076	43.2	704	0.061	130
6	Klondike Rose	46.9	508	0.092	43.7	508	0.086	138
7	Russet Burbank	48.5	572	0.085	40.9	518	0.079	43
8	Russet Norkotah CO#3[b]	47.9	521	0.092	50.9	480	0.106	45
9	Russet Norkotah CO#3	47.0	518	0.091	46.0	577	0.080	109
10	Russet Burbank	53.2	521	0.102	51.0	605	0.084	130
11	Russet Norkotah TXNS112	48.9	531	0.092	45.1	582	0.077	65
12	Russet Norkotah TXNS278	55.7	584	0.095	48.8	607	0.080	138
13	Russet Norkotah	43.8	335	0.131	55.0	422	0.131	81
14	Russet Norkotah	44.9	358	0.126	42.7	455	0.094	129
15	Russet Burbank	34.7	437	0.080	43.2	437	0.099	130
16	Alturas	43.9	546	0.080	42.6	546	0.078	16
17	Russet Norkotah	46.3	457	0.101	38.2	457	0.084	123
18	Ranger Russet	33.6	493	0.068	40.9	465	0.088	126
19	Ranger Russet	49.8	442	0.113	43.7	478	0.092	126
20	Russet Norkotah CO#3	51.6	533	0.097	47.9	589	0.081	85
21	Russet Burbank	46.5	582	0.080	49.9	635	0.079	85
22	Russet Norkotah	43.8	409	0.107	42.7	505	0.084	55
23	Russet Norkotah CO#3	51.2	605	0.085	47.1	605	0.078	57
24	Russet Burbank	52.8	404	0.131	46.9	480	0.098	85
25	Russet Norkotah CO#3	58.8	495	0.119	57.2	483	0.118	83
26	Ranger Russet	44.8	445	0.101	47.6	483	0.099	118
27	Russet Norkotah	44.8	406	0.110	42.0	457	0.092	69
28	Russet Norkotah CO#3	58.8	457	0.129	46.5	495	0.094	105
29	Russet Burbank	54.9	521	0.105	53.2	546	0.097	123
30	Russet Norkotah CO#8	38.1	419	0.091	41.5	483	0.086	87
31	Russet Norkotah	52.7	445	0.119	47.6	483	0.099	89
	Average	48.4	486.0	0.102	45.7	513.3	0.091	

[a] Russet Norkotah line selection from Texas breeding program

[b] Russet Norkotah line selection from Colorado breeding program

This indicates that the potato plants used water application amounts through 100% ET for tuber production and that the 100% ET application was the optimum about for tuber production.

Gross Return

In 2006, the interactions between N treatments and planting systems (N × PS, Table 3) and irrigation and N treatments were significant for gross return (I × N, Table 3). Gross return for the 7-row bed system was significantly greater than for the 5-row bed system for all N treatments applied after tuber initiation (50, 100 and 150% of recommended N) (Fig. 8). Gross return for the 7-row bed system was also significantly greater than for the ridged-row system for the 100% of recommended N rate. Gross return was \$759 ha^{-1} greater with the 7-row bed system than the 5-row bed system when averaged over the three N treatments applied after tuber initiation. The significant increase in gross return is due to a decrease in tuber size obtained from the 5-row bed system (data not shown). Smaller size tubers translated into lower gross return using the 2006 fresh pack price structure of Table 1. Gross return for the 50, 100 and 150% of recommended N treatments were significantly greater than for the <20% of recommended N treatment for all but the 50% and 100% ET irrigation treatments (Fig. 8).

In 2007, the interaction between irrigation and N treatments was significant for gross return (Fig. 9). The interaction was significant for the 85% and 130% ET irrigation treatments only. For the 85% ET irrigation treatment, gross return for the 50% of recommended N rate was greater than for either the 100% or 150% of recommended N rates. This is the result of the same significant interaction for total yield (Fig. 4). The higher gross returns in 2007 relative to 2006 were a result of higher potato prices in 2007 relative to 2006 (Table 1). Substantial above normal temperatures in the region in 2007 which lead to potato tuber quality issues and reduced yields in 2007 was partially responsible for higher potato prices in 2007.

Commercial Fields

Results from bed planting system field trials on 31 commercial fields in eastern Idaho representing a combined area of 2,800 ha from 2005 through 2009 are shown in Table 4. Plant populations varied by producer and cultivar and were not recorded. All the commercial field trials used the 5-row bed planting system. The 7-row bed planting system is too much of a cultural production practice change for producers to readily adopt on a field scale. The 7-row bed planting system has been successfully used on small specialty potato cultivars but confidentiality of field trial results prevents publication of data. Commercial field comparisons of mean, total yield, water application, and irrigation water use efficiency were significantly different ($p \leq 0.05$) between the 5-row bed system and ridged-row planting. The 5-row bed system averaged 6% higher total yield, 5% less water application and an 11% increase in irrigation water use efficiency. Use of the 5-row bed system did not always result in a positive outcome; however there were a greater number of positive outcomes than negative outcomes. Based on the number of published studies, irrigated potato production in a bed system has been the subject of limited research and has had little opportunity for optimization. Despite this lack of research, potato producers in eastern Idaho have been able to take advantage of the 5-Row bed system to increase yield and reduce irrigation water use. The results are encouraging and the outlook for continued development and adoption of bed systems for irrigated potato production in eastern Idaho is positive.

Conclusions

The results of this study show that 5-row and 7-row 3.7 m wide bed planting systems can be used for irrigated production of Russet Norkotah potatoes without sacrificing yield or quality under high intensity sprinkler irrigation in the soil and climatic conditions prevalent in eastern Idaho. Planting potatoes in wide beds may improve water and nitrogen use efficiency due to a reduction in the amount of infiltration in the furrow, beyond the extent of much of the potato root zone. The wide bed planting systems provide a new opportunity to manipulate plant spacing to maximize use of available water and nutrient resources as well as target specific potato markets based on tuber size. Optimum plant population is likely a key issue to be resolved in order to make wide bed planting systems economically advantageous relative to conventional ridged-row planting. Optimum plant population may be cultivar and target market specific. Additional research on soil water and nitrogen dynamics in wide bed systems is needed to fully exploit potential increases in water and nitrogen use efficiency.

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Appendix

Sample SAS program used to test significance of main effects of planting system, irrigation level, N application rate interactions on yield, irrigation water use efficiency and gross return. Program variable names are: Irrig = irrigation rates, Row = planting systems, N = nitrogen rates, irr_rep = irrigation randomization, Blk = planting strip block, yldtot = measured total yield. The SAS program used is below:

```
proc mixed data=work.yield_data;
class Irrig Row N irr_rep Blk;
model yldtot = Irrig|Row|N/ddfm=kr;
random irr_rep Blk(irr_rep) Irrig*irr_rep Row*Blk Irrig*Row*Blk;
lsmeans Row*N/diff;
ods output diffs=mndiffs;

data mndiffs2;set mndiffs;
if N=_N and Row=4;

proc print data= mndiffs2;
var N Row _Row estimate- -probt;

quit;
```

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