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Effects of Planting Configuration and In-Row Plant Spacing on Photosynthetically Active Radiation Interception for Three Irrigated Potato Cultivars

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Abstract Research studies have evaluated the production of potatoes (*Solanum tuberosum* L.) grown in conventional and bed planting configurations. However, intercepted photosynthetically active radiation (PAR) from these planting configurations has not been quantified. A study conducted in 2008 and 2009 quantified and compared the intercepted PAR from three planting configurations (four row conventional ridged-row [4RC], five row bed [5RB], and seven row bed [7RB]), and from different plant spacings of cvs Russet Burbank, Russet Norkotah, and Ranger Russet potatoes under sprinkler irrigation. A second study was conducted in 2007 to evaluate the relationship between PAR and leaf area of Russet Norkotah and Russet Burbank for the three planting configurations. These studies were conducted at the USDA-ARS Northwest Irrigation & Soils Research Lab in Kimberly, ID, on a Portneuf silt loam (coarse–silty mixed mesic Durixerollic Calciorthid). The canopy of Russet Norkotah and Ranger Russet potatoes grown in 5RB and 7RB planting configurations intercepted more PAR during the early vegetative and tuber initiation growth stages compared to the 4RC planting configuration at equal populations in 2008 and 2009 at all measurement dates. The canopy of Russet Burbank intercepted more PAR during the early growth stage in 2008 when planted in the bed planting configurations compared to the 4RC planting configuration, but not on the July 17, 2008 and July 9, 2009 dates. The canopy cover of Russet Burbank potatoes planted in the 4RC planting configuration tended to catch up with the bed planting configurations quicker than the other two cultivars. In general, the quantity of PAR intercepted as affected by planting configuration did not influence total tuber yield and other measured production variables. Cumulative PAR interception 0–72 days after

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planting (DAP) was increased 35%, 38%, and 32% for the 5RB and 65%, 69%, 23% for the 7RB relative to the 4RC planting configuration for Ranger Russet, Ranger Norkotah, and Russet Burbank, respectively. Cumulative PAR interception for the season was increased 15%, 16%, and 4% for the 5RB and 23%, 23%, 5% for the 7RB relative to the 4RC planting configuration for Ranger Russet, Ranger Norkotah, and Russet Burbank, respectively. The relationship between intercepted PAR and leaf area for Russet Norkotah during the early vegetative and tuber initiation growth stages was significantly different between the three planting configurations, with intercepted PAR at a given leaf area in the order of 7RB>5RB>4RC. For Russet Burbank, the relationship was significantly different for the 5RB and 7RB compared to 4RC planting configuration only, with intercepted PAR at a given leaf area in the order of 7RB=5RB>4RC.

Keywords Bed · In-row spacing · Photosynthetically active radiation · Planting configuration · Potato · Ranger Russet · Russet Burbank · Russet Norkotah · *Solanum tuberosum*

Introduction

There may be advantages to planting potatoes (*Solanum tuberosum* L.) in bed configurations compared to conventional ridged-rows. Compared to conventional ridged-row planted potatoes, research has shown that potatoes planted in beds have comparable production output (Nelson 1967; Wayman 1969; Thompson et al. 1974; Alva et al. 2002; Tarkalson et al. 2011), greater yields and net return (Prestt and Carr 1984; McKeown 1987; Fisher et al. 1993; King et al. 2011), increased rate of potato emergence (Prestt and Carr 1984), more uniform water distribution in the root zone (Prestt and Carr 1984; Robinson 1999; Essah and Honeycutt 2004), reduced runoff and erosion (Prestt and Carr 1984; Robinson 1999; Alva et al. 2002; Essah and Honeycutt 2004), and greater water use efficiency (Fisher et al. 1993; King et al. 2011).

Prior to 1940 in irrigated areas of the USA, the conventional ridged-row planting system provided a convenient furrow between potato rows for water distribution by surface irrigation. Over the past 60 years, irrigation technology and irrigated potato production practices have substantially changed. Yet, the basic ridged-row planting configuration for commercial irrigated potato production remained unchanged. Currently, potato production in the Pacific Northwest, which produces over 50% of the US fall potato crop, is essentially all sprinkler-irrigated (Pehrson et al. 2010; King et al. 2011). The traditional ridged-row planting configuration is no longer necessary for irrigation water distribution and may actually be antagonistic to efficient water management under high application rate sprinkler irrigation (center pivot). Runoff from the sides of the 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. 1976; Waddell et al. 2000).

Research has demonstrated that interception of solar radiation is related to the total yield of many crops (Sibma 1970) and the efficiency of assimilation into dry matter (Haverkort et al. 1991). Total potato dry matter production has been found to be linearly related to seasonal cumulative photosynthetically active radiation (PAR) (400–700 nm) interception across different environments (Khurana and McLaren 1982; Fahem and Haverkort 1988; Jefferies and MacKerron 1989; Manrique et al. 1991). Similarly, potato tuber dry matter yield has been found to be linearly related to cumulative PAR interception (Khurana and McLaren 1982; Fahem and Haverkort 1988; Jefferies and MacKerron 1989; Haverkort and Harris 1986; Boyd et al. 2002). In their study of the influence of leaf area and light interception on potato growth and yield, Khurana and McLaren (1982) found that PAR interception increased sharply with increasing leaf area up to values of 2.25, then continued to increase at a slower rate up to a leaf area of 4 at which point around 95% of incoming radiation was intercepted. This, along with the strong correlation between cumulative PAR interception and tuber yield, lead Khurana and McLaren (1982) to conclude that to maximize tuber yield, a rapidly developing canopy to a leaf area of 3.5–4.0 is required along with maintaining the developed canopy free from water, nutrient, and pest stresses. Research has shown that there is often a significant quadratic relationship between light interception and leaf area in potatoes (Firman and Allen 1989; Burstall and Harris 1983). This relationship is explained by a fairly linear relationship early in the season as the canopy develops prior to full ground cover, then at around the time of full ground cover (high light interception), there is continued increase in leaf area production from plant growth. Planting potatoes in beds, which allows for greater flexibility in plant spacing architecture by adjusting between and in-row spacing, may provide an opportunity to interception more seasonal radiation and increase yield for some potato cultivars.

The potential benefits from planting potatoes in beds rather than ridged-rows has lead to the development of two wide bed potato planting configurations being tested in Idaho by Western Ag Research (Blackfoot, ID, USA). The bed planting configurations are both 3.658 m wide with either: (1) five rows spaced 66 cm apart centered on the bed, or (2) seven rows equally spaced 46 cm apart. The 3.658 m bed width was selected to be compatible with existing four-row (0.9144 m row spacing) conventional potato harvesting equipment. Potato planters for both wide bed planting configurations are currently commercially available from Harriston Industries (Minto, ND, USA) and Spudnik Equipment Company (Blackfoot, ID, USA). Over the past 5 years of research and development, several thousand hectares of potatoes have been planted using the wide bed planting configurations as a result of on-farm studies conducted by Western Ag Research. Overall, the results have been positive in regards to enhancing potato yield and quality, and increasing irrigation water use efficiency (King et al. 2011). Several producers have reported seasonal water application reductions of 10% to 1% relative to conventional ridged-row planted potato fields with equal or better potato tuber yield and/or quality.

No data exists to quantify the interception of photosynthetically active radiation of potatoes within bed planting configurations. Tarkalson et al. (2011) conducted a study to evaluate the effect of in-row plant spacing on the production of Russet Burbank, Russet Norkotah, and Ranger Russet potatoes planted in four row conventional ridged-row (4RC), five row bed (5RB), and seven row bed (7RB) planting configurations under sprinkler irrigation. The current paper will quantify and compare the intercepted PAR from the planting configurations and plant spacing treatments reported in Tarkalson et al. (2011) and from an independent second study and how these are related to measured production variables.

Materials and Methods

Study 1: Treatments and Study Design

Quantity of PAR interception by three potato cultivars under three planting configurations and various in-row spacings was measured in a field study conducted during 2008 and 2009 at the USDA-ARS Northwest Irrigation & Soils Research Lab in Kimberly, ID on a Portneuf silt loam (coarse–silty mixed mesic Durixerollic Calciorthid). Specifics of this study design are described in Tarkalson et al. (2011). In summary, three cultivars were evaluated: Russet Burbank, Russet Norkotah, and Ranger Russet. Treatments within these varieties consisted of three planting configurations (4RC, 5RB, and 7RB), and three in-row plant spacings for each planting configuration (Table 1). The bed planting systems were both 3.7 m wide with either: (1) five rows spaced 66 cm apart centered on the bed, or (2) seven rows equally spaced 46 cm apart. The 3.7 m bed width was selected to be compatible with existing four-row (0.91 m row spacing) conventional ridged-row potato harvesting equipment. Plant spacings for the planting configurations were based on published recommendations (4RC) (Bohl et al. 2003) and best scientific judgment (5RB and 7RB) since

Table 1 In-row plant spacing and plant populations of planting configurations for Russet Burbank, Russet Norkotah, and Ranger Russet potatoes in 2008 and 2009

Cultivar	Planting configuration	In-row plant spacing (cm)	Plant population (plants ha^{-1})
Russet Burbank and Russet Norkotah	4RC	20.32	53,800
		30.48	35,900
		40.64	26,900
	5RB	29.21	46,800
		33.02	41,400
		38.10	35,900
	7RB	41.15	46,500
		46.48	41,200
		53.34	35,900
Ranger Russet	4RC	17.78	61,500
		27.94	39,100
		38.10	28,700
	5RB	26.92	50,800
		30.48	44,900
		35.00	39,100
	7RB	37.59	50,900
		42.42	45,100
		49.02	39,100

4RC four row conventional ridged-row planting configuration, *5RB* five row bed planting configuration, *7RB* seven row bed planting configuration

no research has been conducted to determine the optimum in-row plant spacings in order to give a potential range around the optimal population for production. For the 4RC planting configuration, the middle plant spacing treatment for each cultivar was based on recommendations from Bohl et al. (2003) and the other two spacing treatments were approximately 10 cm greater and less than the recommended spacing. For the 5RB and 7RB planting configuration treatments, the widest in-row plant spacing was set to equal the plant population given by the middle in-row plant spacing treatment of the 4RC planting configuration for each cultivar. The middle and narrowest in-row plant spacings for the bed planting configurations were established by decreasing the widest in-row plant spacing by approximately 13% and 30%. Plot size was 3.7 m wide and 7.6 m long. Cultivars, planting configuration, and in-row plant spacing treatments were arranged in a three-way factorial randomized block statistical design with four replications.

Study 1: Photosynthetically Active Radiation Interception Measurements

Light interception by the potato crop canopy in each plot was measured on July 1, July 8, and July 17 in 2008 and on July 9 in 2009 using an LI-191SA line quantum sensor connected to a LI-250A light meter (LI-COR, Inc. Lincoln, NE, USA). The LI-191SA line quantum sensor measures PAR in the 400 to 700 nm waveband on a plane surface. Measurements were taken at two locations in each plot during each measurement date. Measurements were taken parallel to the ground surface above the plant canopy to quantify total incoming PAR and below the canopy on the soil surface to quantify PAR passing through the canopy. The ends of the sensor were placed in the middle of adjacent potato rows. The fraction of PAR intercepted was calculated by dividing the soil surface value by the above canopy value (Frederick et al. 1998). To ensure continuity in the data, measurements were made between 1 h before and after solar noon on days with no cloud cover (Tollenaar and Bruulsema 1988). Measurements were recorded after readings stabilized. Measurement dates were all during the early vegetative and tuber initiation growth stages. Light interception measurements were discontinued after mid-July because they become unreliable when the canopy begins to senesce or lodge (Burstall and Harris 1983). The line quantum sensor cannot distinguish between living leaves and other material. When potato vines lodge, they tend to form clumps (Burstall and Harris 1983) which makes it difficult to take reliable measurements. The vines have to be manually lifted from the furrows (4RC) to place the sensor below the canopy which disturbs natural canopy structure.

Study 1: Potato Harvest

Prior to harvest, potato vines were killed with a desiccant spray (diquat dibromide). Tubers were harvested with a conventional four-row potato windrower on September 25 and 23 in 2008 and 2009, respectively. An area 3.7 m wide by 4.9 m long was harvested from each plot and total tuber yield, U.S. No. 1 tuber yield, percent U.S. No. 1 tubers, average tuber size, and marketable yield were measured. U.S. No. 1 potatoes are not defined based on size, but rather broadly defined as potatoes that have similar varietal characteristics, are firm, clean, well-shaped and free from growth cracks, disease and harvest damage.

Study 1: Data Analysis

Plant spacing comparisons of PAR interception at each measurement date were conducted within each cultivar and planting configuration. Planting configuration comparisons of PAR interception at each measurement date were conducted within each cultivar at a plant spacing that produced the same plant population (plant spacing treatments 30, 38, and 53 cm) for the 4RC, 5RB, and 7RB planting configurations, respectively, in Russet Burbank and Russet Norkotah, and 28, 35, and 49 cm for the 4RC, 5RB, and 7RB planting configurations, respectively, in Ranger Russet (Table 1). Analysis of variance was conducted using the Completely Randomized Model from Statistix 8 (Analytical and Software 2003). The least significant difference method was used for mean separations. Regression analysis was used to determine correlations between potato production variables and fraction of PAR intercepted influenced by planting configuration and in-row plant spacing. To determine the influence of intercepted PAR on production of potatoes, within cultivar intercepted PAR from all planting configuration plots with the same plant population were related to individual production variables. Regression analysis was carried out in Microsoft Excel. Significance was determined at the 0.05 probability level for all analyses.

Study 2

A 1-year dataset (2007) was used to evaluate the relationship between PAR and leaf area by Russet Norkotah and Russet Burbank for different planting configurations. In 2007, the cultivars were grown under 4RC, 5RB, and 7RB planting configurations and variable plant spacings at the USDA-ARS Northwest Irrigation & Soils Research Lab in Kimberly, ID on a Portneuf silt loam. Leaf area was determined by sampling three plants from each plot. All leaves were taken from the plants and leaf area was measured summing the area of all leaves using a LI-COR LI-3100 Area Meter (LI-COR, Inc. Lincoln, NE, USA). Leaf area was calculated (per hectare basis) by multiplying the average measured leaf area per plant by the total population of the plot (per hectare basis). Because spacing had no effect on PAR interception, leaf area and PAR readings were averaged over all plant spacings for each cultivar and planting configuration. The average plant population for each cultivar and planting configuration was approximately 41,000 plants ha^{-1}. The 5RB planting configuration was planted on April 17, 2007 and the 4RC and 7RB planting configurations were planted on April 19, 2007. Two sampling dates, June 8 and June 26, 2007, were used to develop relationships between PAR and leaf area during the early vegetative and tuber initiation stages of growth. The method to determine PAR in 2007 was the same as described earlier for 2008 and 2009.

The fraction of incident PAR transmitted through the canopy was modelled using Lambert–Beer equation:

$$I = I_o e^{-k(\mathrm{LAI})} \tag{1}$$

Where I is the irradiance on a horizontal plane below a canopy with a leaf area index of LAI, and k is a light extinction coefficient, assuming a homogenous canopy and I_o is the irradiance directly above the canopy (Khurana and McLaren 1982; Manrique et al. 1991; Boyd et al. 2002). The light extinction coefficient was represented as a linear function of LAI, which was found to provide the best overall relationship between k and LAI. Fraction of PAR intercepted by the canopy was calculated as $1 - e^{-(a+b(\mathrm{LAI}))(\mathrm{LAI})}$. Khurana and McLaren (1982) found that k varied with LAI and used a quadratic equation to relate k to LAI. The coefficients of the equation for fraction of PAR (a and b) were determined using nonlinear regression techniques (sum of squares reduction test, PROC NLIN, SAS 2007). Significant differences in the PAR and LAI relationship between planting configurations were determined by comparing coefficient 95% confidence intervals between each planting configurations. Data for a sampling date and plant spacing were combined for development of PAR interception models for each planting configuration and cultivar.

The relative difference in cumulative 2008 seasonal intercepted PAR was estimated by modelling PAR interception over the growing season for each cultivar and planting configuration. Photosynthetically active radiation interception was modelled from emergence (37 days after planting (DAP)) to 72 DAP using cubic spline interpolation of field measurements of PAR interception. PAR interception was assumed constant from 72 to 100 DAP as this duration corresponds to the duration of maximum leaf area for climatic conditions under stress free conditions (Kleinkopf et al. 1981). Interception of PAR from 100 to 128 DAP was approximated by a linear decrease to an ending value of 25%. The resulting piecewise approximation of PAR interception closely follows the model by Kooman et al. (1996) used to represent PAR interception during the growing season. This procedure assumes that maximum PAR interception was achieved by 72 DAP, duration of maximum PAR interception was equal for all planting configurations of a cultivar, and the rate of senescence was equal for all planting configurations of a cultivar. Thus, any planting configuration effect on maximum PAR interception or rate of senescence will not be captured by this approach. Photosynthetic active radiation interception rates for the last sampling date in 2008 exceeded 90% for all but one of the treatments. Firman and Allen (1989) found that maximum PAR interception rates were not much more than 90%, regardless of canopy density. Thus, the assumption that maximum PAR interception rates were attained is reasonable.

Incident PAR was calculated assuming 45% of the total solar radiation as PAR (Meek et al. 1984). Cumulative seasonal PAR was calculated as the product of incident PAR and PAR interception on a daily basis summed 0–128 DAP.

Results and Discussion

Effect of Planting Configuration on PAR Interception

Planting configuration affected the quantity of PAR intercepted by the potato canopy early in the growing season, with the bed planting configurations intercepting more PAR than the 4RC planting configuration. The canopy of Russet Norkotah and

Ranger Russet potatoes grown in 5RB and 7RB planting configurations intercepted more PAR than the 4RC planting configuration at equal populations at most dates in 2008 and 2009 (Fig. 1). The potato canopy of Russet Burbank intercepted more PAR during the early part of 2008 when planted in the bed planting configurations compared to the 4RC planting configuration, but not on July 17, 2008 and July 9, 2009. The canopy cover of Russet Burbank potatoes planted in the 4RC configuration tended to catch up with the bed panting configurations quicker than the other two cultivars. These data may help explain the findings from Tarkalson et al. (2011), where Russet Norkotah and Ranger Russet potato production under the bed planting configurations were not significantly different from conventional ridged-row planting

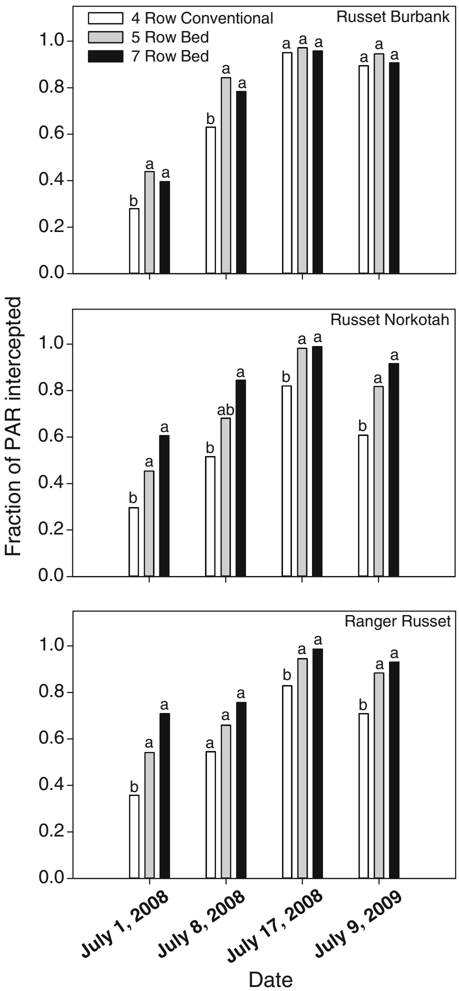

Fig. 1 Effect of planting configuration on fraction of photosynthetically active radiation (PAR) intercepted in Russet Burbank, Russet Norkotah, and Ranger Russet potatoes on selected dates in 2008 and 2009. Comparisons of planting configuration treatments were made at the same plant populations for each planting configuration. For each date, planting configurations with the same letter are not significantly different as $P<0.05$

but evidence suggested that production of Russet Burbank may be better suited under the 4RC planting configuration.

Significant differences in measured PAR between planting configurations (Fig. 1) resulted in differences in modelled PAR interception 0–72 DAP between the bed planting configurations. The Russet Burbank cultivar is characterized as having a large, vigorous, and spreading vine (Pavlista 2010) which explains why it is able to develop sufficient canopy to intercept essentially all incident PAR regardless of planting configuration for evaluated plant spacings (Fig. 1). The Norkotah Russet cultivar is characterized as having a medium-sized upright vine resulting in about 85% row closure and the Ranger Russet cultivar is characterized as a medium-large plant (Pavlista 2010). Based on visual observation, neither cultivar achieved full row closure with the 4RC planting. For all three cultivars prior to 72 DAP, the order of planting configurations in regards to increasing PAR interception was 4RC<5RB<7RB (Table 2). Relative differences in cumulative PAR interception between planting configurations prior to 72 DAP were similar for both the Russet Norkotah and Ranger Russet cultivars (Table 2) with the 5RB having 44% and the 7RB having ~60% greater cumulative PAR interception compared to the 4RC planting configuration for the evaluated plant spacings. For the Russet Burbank cultivar, relative differences in cumulative PAR interception between planting configurations prior to 72 DAP were 32% greater for the 5RB and 47% greater for the 7RB relative to the 4RC planting configuration. Relative differences in seasonal cumulative PAR interception between planting configurations were similar for both the Russet Norkotah and Ranger Russet cultivars (Table 2) with the 5RB having 17% and the 7RB having ~21% greater cumulative PAR interception than the 4RC planting configuration. For the Russet Burbank cultivar, relative differences in seasonal cumulative PAR interception between planting configurations were 8% greater for the 5RB and 11% greater for the 7RB relative to the 4RC planting configuration. Based on estimated seasonal cumulative PAR interception, bed planting potato cultivars that have medium-sized vines that are upright have the greatest potential of a yield increase relative to 4RC planting.

Table 2 Modeled early season and total seasonal cumulative photosynthetically active radiation (PAR) interception (MJ m^{-2}) for three potato cultivars and three planting configurations at Kimberly, ID in 2008 based on means of measured PAR (Fig. 1)

Time duration		Russet Burbank			Russet Norkotah			Ranger Russet		
		4RC	5RB	7RB	4RC	5RB	7RB	4RC	5RB	7RB
0–72 DAP		168	222	207	159	219	269	177	240	292
	%diff [a]		32	23		38	69		35	65
Season		703	750	741	651	754	803	670	774	826
	%diff [a]		4	5		16	23		15	23

Modelled data is based on the same plant populations for each planting configuration

4RC four row conventional ridged-row planting configuration, *5RB* five row bed planting configuration, *7RB* seven row bed planting configuration, *DAP* days after planting

[a] Percent difference relative to 4RC

Effect of Plant Spacing on PAR Interception

Russet Burbank potato in-row plant spacing in the 4RC planting configuration had a greater effect on intercepted PAR than in the bed planting configurations (Table 3). For three of the four PAR measurement dates, as in-row spacing decreased from 41 to 20 cm (increased population), intercepted PAR increased in the 4RC planting configuration treatment. There was little effect of plant spacing on intercepted PAR in the bed planting configurations for Russet Burbank. In general, Russet Norkotah and Ranger Russet potato plant spacing under all planting configurations had little influence on intercepted PAR (Tables 4 and 5).

Effect of Changing PAR Interception as a Result of Planting Configuration on Potato Production Variables

When comparing the linear relationship between the quantity of PAR intercepted during the 2008 season and potato production variables (total tuber yield, U.S. No. 1 tuber yield, average tuber size, and tuber count) as affected by planting configuration at equal populations, (35,900 plants ha^{-1} for Russet Burbank and Russet Norkotah, and 39,100 plants ha^{-1} for Ranger Russet), there were only few significant relationships (Fig. 2). However, we did not quantify the ability of the plants to convert the intercepted radiation to tuber dry matter. This aspect of the system needs to be better understood and measured to fully understand the above canopy influence on potato production. In potatoes, the underground along with aboveground systems jointly play important roles in development of yield in potatoes.

Table 3 Effect of in-row plant spacing of cv. Russet Burbank on fraction of photosynthetically active radiation interception for three planting configurations on different dates in 2008 and 2009

Planting configuration	In-row plant pacing cm	July 1, 2008	July 8, 2008	July 17, 2008	July 9, 2009
4RC	20	0.299	0.679 a	0.974 a	0.902 a
	30	0.280	0.630 a	0.951 a	0.895 a
	41	0.237	0.437 b	0.850 b	0.784 b
	Mean	0.272	0.582	0.925	0.860
	P value	0.5439	0.0300	0.0459	0.0351
5RB	29	0.414	0.746	0.986	0.900 b
	33	0.413	0.831	0.973	0.943 a
	38	0.440	0.843	0.972	0.946 a
	Mean	0.422	0.807	0.977	0.930
	P value	0.4333	0.2871	0.1398	0.0063
7RB	41	0.615 a	0.885	0.982	0.975
	46	0.495 ab	0.918	0.989	0.936
	53	0.396 b	0.784	0.958	0.907
	Mean	0.502	0.862	0.976	0.939
	P value	0.0191	0.0648	0.1841	0.3417

Values in the same column within each planting configuration with the same letters are not significantly different at the 0.05 probability level.
4RC four row conventional ridged-row planting configuration, *5RB* five row bed planting configuration, *7RB* seven row bed planting configuration

Table 4 Effect of in-row spacing of cv. Russet Norkotah on fraction of photosynthetically active radiation interception of in-row plant spacing treatments for three planting configurations on different dates in 2008 and 2009

Planting configuration	In-row plant spacing cm	July 1, 2008	July, 8 2008	July 17, 2008	July 9, 2009
4RC	20	0.315	0.595	0.907	0.693 a
	30	0.296	0.516	0.820	0.608 a
	41	0.271	0.437	0.849	0.469 b
	Mean	0.294	0.516	0.859	0.590
	P value	0.7121	0.0887	0.2813	0.0031
5RB	29	0.530	0.702	0.979	0.853
	33	0.503	0.827	0.967	0.870
	38	0.454	0.681	0.982	0.817
	Mean	0.496	0.737	0.976	0.847
	P value	0.2337	0.0843	0.4154	0.7443
7RB	41	0.579	0.867	0.988	0.912 a
	46	0.549	0.781	0.984	0.877 b
	53	0.606	0.844	0.989	0.916 a
	Mean	0.578	0.831	0.987	0.902
	P value	0.8009	0.7336	0.7067	0.0350

Values in the same column within each planting configuration with the same letters are not significantly different at the 0.05 probability level.
4RC four row conventional ridged-row planting configuration, *5RB* five row bed planting configuration, *7RB* seven row bed planting configuration

The greater the quantity of PAR intercepted during the 2008 season by Russet Norkotah and Ranger Russet potatoes across planting configurations at the same population, the smaller the average tuber size (Fig. 2). At the first two measurements of intercepted PAR, there were trends for increased tuber numbers with increased

Table 5 Effect of in-row spacing of cv. Russet Ranger on fraction of photosynthetically active radiation interception for three planting configurations on different dates in 2008 and 2009

Planting configuration	In-row plant spacing cm	July 1, 2008	July, 8 2008	July 17, 2008	July 9, 2009
4RC	18	0.362	0.592	0.819	0.824 a
	28	0.357	0.545	0.829	0.709 ab
	38	0.337	0.538	0.797	0.605 b
	Mean	0.352	0.558	0.815	0.713
	P value	0.8765	0.6453	0.4783	0.0120
5RB	27	0.614	0.874	0.963	0.913
	30	0.563	0.755	0.979	0.904
	35	0.542	0.659	0.945	0.884
	Mean	0.573	0.763	0.963	0.900
	P value	0.6815	0.0844	0.3894	0.5681
7RB	38	0.722	0.867	0.983	0.945 a
	43	0.639	0.860	0.967	0.910 b
	49	0.708	0.757	0.986	0.931 a
	Mean	0.690	0.828	0.979	0.929
	P value	0.5107	0.3991	0.5953	0.0027

Values in the same column within each planting configuration with the same letters are not significantly different at the 0.05 probability level.
4RC four row conventional ridged-row planting configuration, *5RB* five row bed planting configuration, *7RB* seven row bed planting configuration

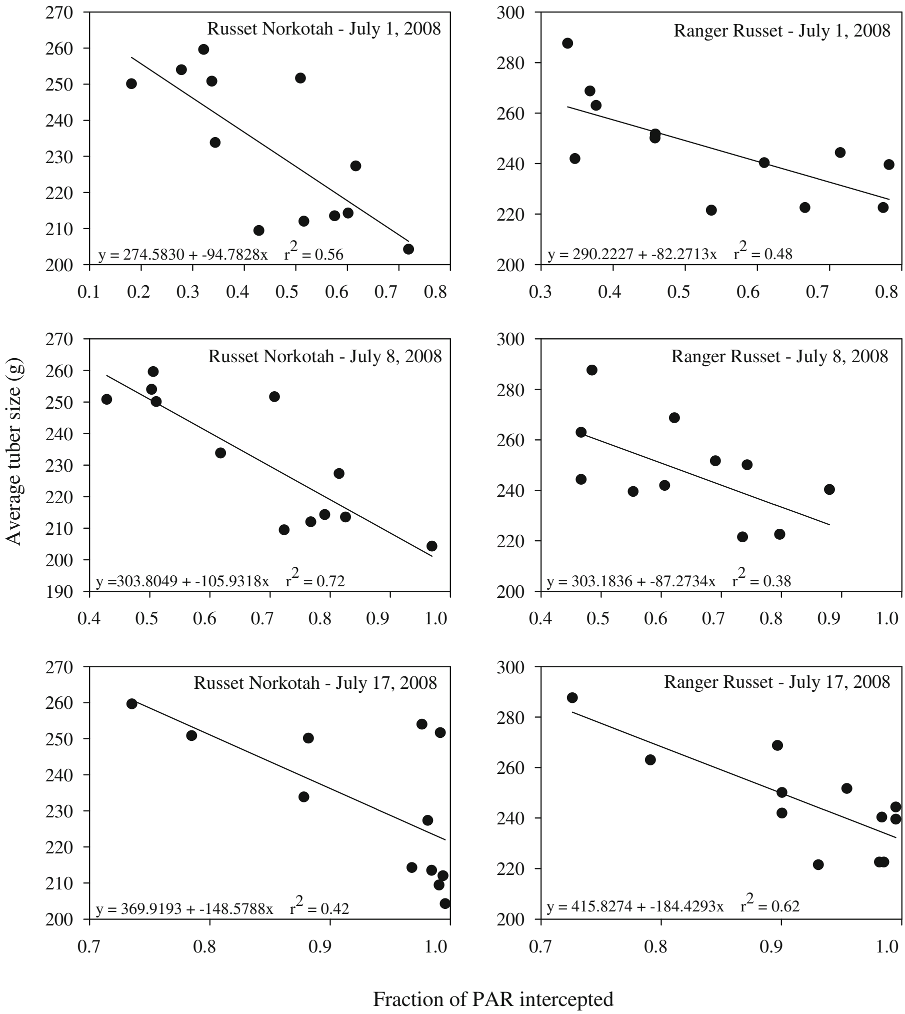

Fig. 2 Relationships between average tuber size and fraction of photosynthetically active radiation (PAR) intercepted for Russet Norkotah and Ranger Russet on July 1, 2008, July 8, 2008, and July 17, 2008. Data points are planting configuration values at the same plant population. All correlations are significant at the 0.05 probability level

interception of PAR for Russet Norkotah and Ranger Russet. This trend was not observed with Russet Burbank at all intercepted PAR measurement dates and with Russet Norkotah and Ranger Russet at the late intercepted PAR measurement dates.

The significant negative correlations for Russet Norkotah and Ranger Russet cultivars between PAR intercepted and tuber size (Fig. 2) were mostly associated with the 4RC planting configuration (Fig. 1) due to a narrower in-row plant spacing to reach a given plant population compared to the bed planting configurations, which resulted in a lower average tuber size. Average tuber size was found to decrease with plant population by Lynch and Rowberry (1977) who studied the effect of plant population (44,000 to 110,000 plants ha^{-1}) on Russet Burbank yield using a square planting arrangement (equal in-row and between-row spacing). They found that total tuber yield did not respond to increased plant population. Lynch and Rowberry (1977) found that LAI in the early vegetative and tuber initiation growth stages increased with plant population. The negative correlation between PAR and tuber size found in this study is largely the result of a negative relationship between plant population and tuber size as intercepted PAR (i.e., LAI) in the early vegetative and tuber initiation growth stages is directly related to plant population.

Planting potatoes in a bed configuration allows for greater cumulative seasonal PAR interception over the growing season. The effect on tuber yield appears to be smaller than predicted based on published radiation use efficiency for the study site. The expected increase in tuber yield was less than could be detected by the experimental design used in this study. Results of on-farm production trials reported by King et al. (2011) indicate that a small tuber yield increase exists with bed planting configurations. Planting potatoes in beds may be one modification to irrigated potato production systems that can increase production efficiency.

Effect of Changing PAR Interception as a Result of Plant Spacing on Potato Production Variables

For each cultivar, there were 36 correlations between measured potato production variables (total tuber yield, U.S. No. 1 tuber yield, and average tuber size) and fraction of PAR intercepted across all plant spacing treatments (three production variables × three planting configurations × four dates in 2008 and 2009 = 36 correlations). Each correlation had a total of 12 data points (each point representing a planting configuration, and replication). In general, the correlations were not significant. For example, Ranger Russet had one of 36 correlations significant. For total tuber yield and all cultivars, only three were significant (Fig. 3). U.S. No. 1 tuber yield and average tuber size were rarely correlated with PAR interception. Of the 108 total correlations for all cultivars and planting configurations, only 9 were significant in which U.S. No. 1 tuber yield increased and average size decreased with increasing fraction of PAR intercepted.

Generally, the amount of PAR intercepted as a result of changing plant spacing was not correlated to production variables with a few exceptions. Increased interception of PAR by potato plants did not translate into increased tuber yield. The quantity of PAR intercepted may influence the average size of Russet Norkotah and Ranger Russet tubers. Intercepted PAR is only one of the environmental factors influencing yield of potatoes. Conversion of the intercepted radiation and conversion to tuber dry matter and belowground systems need to be better elucidated.

Studies have shown that potato dry matter production is linearly related to cumulative intercepted PAR (Khurana and McLaren 1982; Fahem and Haverkort 1988; Jefferies and MacKerron 1989; Manrique et al. 1991) across different environments. Manrique et al. (1991) reported radiation use efficiency (dry matter per unit PAR interception) of 1.7–1.8 $\mathrm{g MJ^{-1}}$ averaged over several cultivars grown at Kimberly, ID. Assuming a constant ratio of tuber fresh weight to total dry matter production of 3.36 for Kimberly, ID (derived from the data of Kleinkopf et al. 1981), a 20% increase in PAR would translate to a fresh tuber yield of 46.3 vs. 38.6 $\mathrm{Mg\ ha^{-1}}$ or a difference of 7.7 $\mathrm{Mg\ ha^{-1}}$. Yield differences of this magnitude across in-row plant spacings were observed but not significant (Tarkalson et al. 2011). The experimental

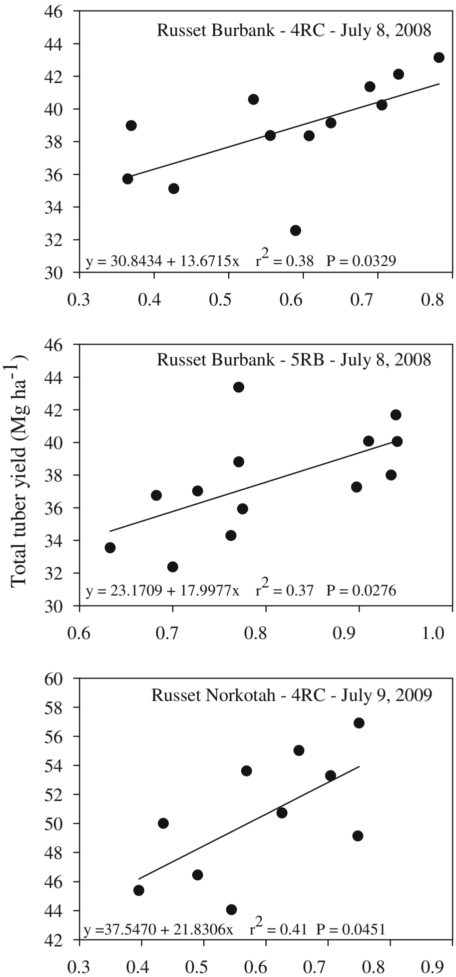

Fig. 3 Relationships between total tuber yield and fraction of photosynthetically active radiation (PAR) intercepted as affected by plant spacing for Russet Burbank planted to the 4RC and 5RB planting configurations on July 8, 2008, and Russet Norkotah planted to the 4RC planting configuration on July 9, 2009. All correlations are significant at the 0.05 probability level

design used in this study was not sufficient to detect expected differences in yield from a 20% increase in cumulative seasonal PAR interception due to inherent potato yield variability and use of only four replicates. However, field trials comparing 5RB against 4RC on 31 fields representing 2,800 ha of commercial irrigated potato production in Idaho and several potato cultivars found a significant increase in total tuber yield and irrigation water use efficiency with 5RB (King et al. 2011). Average total tuber yield increase with the 5RB compared to 4RC in that study was 2.7 Mg ha^{-1}, which is about half the yield increase expected based on increased cumulative seasonal PAR interception of the 5RB planting configuration in this study. However, some of the Russet Norkotah field trials reported by King et al. (2011) had yield increases on the order of 7.7 Mg ha^{-1}. Yield increases resulting from increased cumulative seasonal PAR interception with the bed planting configurations likely exist, but are of a magnitude that makes it difficult to determine with certainty. Realized increases in yield less than that predicted by a 20% increase in cumulative seasonal intercepted PAR may be the result of interplant shading during tuber bulking. The radiation use efficiency reported for Kimberly, Idaho (Manrique et al. 1991) is for a 4RC planting configuration. Changes in planting configuration may affect radiation use efficiency as it changes the relationship between intercepted PAR and LAI (Figs. 4 and 5). Thus, the predicted increase in total dry matter production may not be transferrable across planting configurations. For instance, the slope of the linear correlation between total tuber yield for Russet Burbank on July 8, 2008 (Fig. 3) is different between the 5RB and 4RC planting configurations.

Relationship Between PAR and Leaf Area

The relationship between LAI and PAR interception for Russet Norkotah was significantly different between each planting configuration (Fig. 4). The 4RC planting configuration intercepted the least amount of PAR and the 7RB intercepted the greatest amount of PAR for a given level of LAI during the early vegetative and tuber initiation growth stages. The more spatially distributed plant placement provided by bed planting resulted in reduced competition for light between plants during the early growth stages and potentially throughout the growing season for small-sized potato plants such as the Russet Norkotah cultivar. This may partially be the reason why on-farm production trials reported by King et al. (2011) found that cultivar Russet Norkotah generally had greater yield when planted in a 5RB planting configuration compared to 4RC. The relationship between LAI and PAR interception for Russet Burbank in a 4RC planting configuration was significantly different from the 5RB or 7RB planting configurations (Fig. 5). Planting potatoes in either a 5RB or 7RB configuration resulted in significantly greater PAR interception relative to the 4RC planting configuration for an equivalent LAI (Fig. 5). This is due to greater spatial distribution of plants provided by the bed planting configurations. Greater

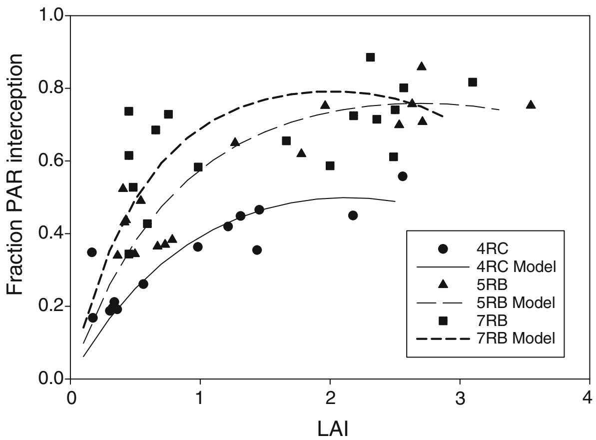

Fig. 4 Relationship between fraction of photosynthetically active radiation (PAR) intercepted and leaf area index (LAI) for Russet Norkotah with each planting configuration

spatial distribution provides each plant an equal opportunity for light for a longer duration early in the growing season. As the growing season progresses and vines continue to grow, interplant shading begins to limit intercepted PAR to each plant. There was no significant difference in the relationship between bed planting configurations. However, the difference between the 4RC and bed planting configurations with Russet Burbank (Fig. 5) was less than with Russet Norkotah (Fig. 4). Interplant shading is expected to be more prevalent in cultivars such as Russet Burbank which is characterized as having a large, vigorous, and spreading vine (Pavlista 2010) in comparison to Russet Norkotah which is characterized as having a medium-sized upright vine (Pavlista 2010). Potato vine growth characteristics of Russet Burbank was the reason the relative increase in cumulative seasonal PAR interception of the 5RB and 7RB compared to the 4RC was approximately a fourth of that for Russet Norkotah and Ranger Russet (Table 2).

Conclusions

The canopy of Russet Norkotah and Ranger Russet potatoes grown in 5RB and 7RB planting configurations intercepted more PAR during the early vegetative and tuber initiation growth stages compared to the 4RC planting configuration at equal populations in 2008 and 2009 at all measurement dates. The potato canopy of Russet Burbank intercepted more PAR during the early growth stage in 2008 when planted in the bed configurations compared to the 4RC planting configuration, but not after early to mid July. The canopy cover of Russet Burbank potatoes planted in the 4RC configuration tended to catch up with the bed planting configurations quicker than the other two cultivars. In general, the quantity of PAR intercepted as affected by planting configuration did not influence total tuber yield and other measured production variables. Cumulative PAR interception 0–72 days after planting (DAP) was increased 45% for the 5RB and 65% for the 7RB relative to the 4RC planting configuration for both Russet Norkotah and Ranger Russet. For Russet Burbank,

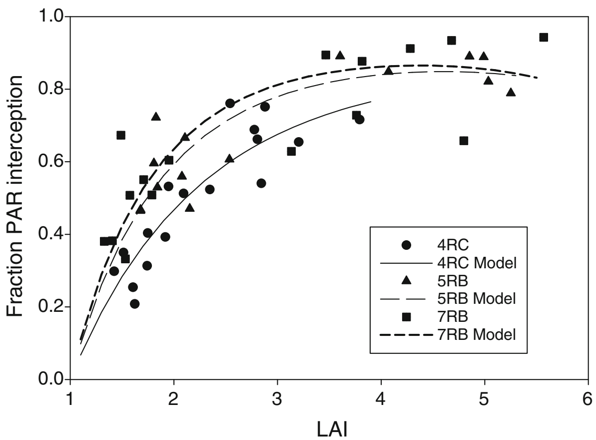

Fig. 5 Relationship between fraction of photosynthetically active radiation (PAR) intercepted and leaf area index (LAI) for Russet Burbank with each planting configuration

cumulative PAR interception 0–72 DAP was increased 32% for the 5RB and 47% for the 7RB relative to the 4RC planting configuration. Cumulative PAR interception for the season was increased 17% for the 5RB and 21% for the 7RB relative to the 4RC planting configuration for both Russet Norkotah and Ranger Russet and 8% for the 5RB and 11% for the 7RB for Russet Burbank. The relationship between intercepted PAR and leaf area for Russet Norkotah during the early vegetative and tuber initiation growth stages was significantly different between the three planting configurations. For Russet Burbank, the relationship was significantly different for the 5RB and 7RB compared to 4RC planting configuration only.

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