Agronomic and Economic Impact of Missing and Irregularly Spaced Potato Plants

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ABSTRACT

Missing and irregularly spaced potato plants compromise grower revenue. A recent survey of 70 commercial fields in Washington State, USA, indicated that in-row seedpiece and plant spacing was irregular due to multiple planter skips and clumped seedpieces. Seven percent (2950 missing plants ha^{-1}) of the intended stand was missing: 6% from planter skips and 1% from non-viable seedpieces. To estimate economic loss to Washington potato growers, two potato (*Solanum tuberosum*) cultivars, Russet Burbank and Russet Norkotah, were grown in small-plot experiments designed to mimic spacing errors commonly found in Washington fields. Yield and economic values of uniform (optimum) spacing were compared to values coming from treatments that simulated planter skips/missing plants and seed clumps (doubles) in 2001 and 2002. The planter-skip treatments produced the lowest total, market, and U.S. No. 1 yields for both cultivars. In-row plants on both sides of a skip collectively compensated for 56% to 67% of the missing plant's economic value. Plants in adjacent rows failed to compensate for their missing neighbor. Doubles reduced average tuber size for both cultivars compared with optimum spacing. Using processing market values, 2950 missing Russet Burbank plants ha^{-1} reduced seed-cost-adjusted gross income 2.9% or \$205 ha^{-1}. Doubles did not affect Russet Burbank processing value. Using fresh market values, 2950 missing and 1980 doubles ha^{-1} reduced Russet Norkotah adjusted gross income 4.4% or \$250 ha^{-1}. Improved planter technology and management efforts would likely improve plant spacing in commercial fields and in turn, grower revenue. Planter manufacturers and growers should consider this information when making management decisions.

RESUMEN

Los ingresos del productor se ven comprometidos debido a fallas en la siembra y espaciamiento irregular de las plantas de papa. Una reciente inspección de 70 campos comerciales en el Estado de Washington indica que la distribución de semilla y el espaciamiento en los surcos fue irregular, debido a omisiones múltiples durante la siembra y semilla sembrada en grupos. Faltó el 7% (2950 plantas menos ha^{-1}) de la cantidad esperada: 6% por omisión de plantas y 1% por semilla no viable. Para estimar la pérdida económica de los productores de Washington, se sembraron experimentalmente dos cultivares de papa (*Solanum tuberosum*): 'Russet Burbank' y 'Russet Norkotah' en parcelas pequeñas diseñadas imitando los errores de espaciamiento comúnmente encontrados en los campos de Washington. En 2001 y 2002 se comparó el rendimiento y valor económico en un espaciamiento uniforme (óptimo) con valores provenientes de los tratamientos que simularon las omisiones/plantas faltantes y la semilla en grupos (dobles). Para ambos cultivares, los tratamientos con omisiones produjeron los rendimientos totales más bajos, comerciables y U.S. No. 1. Las plantas en las hileras a ambos lados de la omisión compensaron de 56% a 67% el valor económico de las plantas faltantes. Las plantas en hileras adyacentes no compensaron las pérdidas de las plantas vecinas. En ambos cultivares, el espaciamiento óptimo de las semillas dobles, redujo el promedio del tamaño del tubérculo. Utilizando los valores del mercado para procesamiento, las 2950 plantas ha^{-1} redujeron el ingreso bruto en 2.9% o \$250 ha^{-1}. La semilla doble no afectó el valor de proce-

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samiento de Russet Burbank. Utilizando los valores de comercialización en fresco, las 2950 plantas faltantes y 1980 dobles ha^{-1} redujeron el ingreso bruto de Russet Norkotah en 4.4% o sea $ 250 ha^{-1}. La tecnología mejorada del agricultor y de manejo probablemente mejoraría el espaciamiento de plantas en campos comerciales y como consecuencia los ingresos. Los agricultores industriales y productores deben considerar esta información al tomar decisiones de manejo.

INTRODUCTION

In 1931, W. H. Martin proclaimed, "missing hills won't pay tax bills" (Martin 1931). Martin referred to non-uniformly spaced potato plants commonly found in New Jersey fields. Sampling potato fields of 10 growers, Martin (1931) discovered 10% to 15% of the intended plant population was missing due to irregular in-row seedpiece placement by mechanical planters. Despite a grower-intended in-row spacing average of 33 cm, actual plant spacing ranged from 8 to 109 cm.

Recent sampling of plant stands in commercial fields in the State of Washington indicates that little has changed with time (Pavek and Thornton 2005). Of 70 fields sampled during 2000, 2001, and 2002, 7% of the intended plant population was missing, 6% from planter skips, and 1% from seed that failed to sprout. In-row spacing was highly variable, with the coefficient of variation (CV) for in-row spacing ranging from 18% to 69%. In comparison, the in-row spacing CV of hand-planted potatoes averaged 13%.

Research as far back as 1919 indicates missing plants and irregular plant spacing can lead to tuber yield loss (Stewart 1919, 1921; Blodgett 1941; Hirst et al. 1973; James et al. 1973; Entz and LaCroix 1984; Sieczka et al. 1986; Thornton et al. 1989; Rupp and Thornton 1989, 1992; Hide et al. 1995, 1996). Yield loss, however, is not always directly proportionate to the number of missing plants. Potato plants often compensate for their missing or irregularly spaced neighbors through increased plant and tuber growth (Stewart 1919, 1921; Hirst et al. 1973; Entz and LaCroix 1984; Sieczka et al. 1986; Hide et al. 1995, 1996).

The degree of yield compensation by neighboring plants depends largely on plant vigor (Hide et al. 1995, 1996), proximity to the missing plant area (Hide et al. 1995, 1996), the area's dimensions (Sieczka et al. 1986), the geographical region, and cultivar (Hirst et al. 1973; Hide et al. 1996). Stewart (1919, 1921) found that each in-row plant on either side of a missing plant compensated for about 25% of the missing plant's total yield. Hirst et al. (1973) indicated that as a result of neighbor plant compensation, yield decline was about 0.32% for every 1% of the plant population missing. In addition, Hide et al. (1995, 1996) reported that most yield compensation came from the immediate in-row plants (first neighbors) on each side of the missing plant. Other in-row plants (second and third neighbors) as well as adjacent-row plants were less important.

Three other studies provide additional evidence of the potato plant's ability to adapt to different spatial arrangements (Pascal et al. 1977; Entz and LaCroix 1984; Sieczka et al. 1986). These studies indicate that uniform in-row spacing is not always essential to optimize yield. In all three studies, yields were similar between irregularly spaced plants (CV levels as high as 80.7%) and uniformly spaced plants (CV levels near 0%). Although yield loss was not detected, changes in spacing often led to changes in tuber size distribution.

Multiple studies indicate missing or irregularly spaced plants affect tuber size profiles (Stewart 1919, 1921; Hirst et al. 1973; Pascal et al. 1977; Entz and LaCroix 1984; Sieczka et al. 1986; Thornton et al. 1989; Rupp and Thornton 1992; Hide et al. 1995, 1996). Changes in tuber size profile can directly affect grower returns (Schotzko et al. 1983, 1984; Thornton et al. 1983, 1989; Rex et al. 1987; Rupp and Thornton 1992; Creamer et al. 1999; Love and Thompson-Johns 1999). Love and Thompson-Johns (1999) reported that seedpieces of russet-type cultivars planted at 8-cm in-row spacing resulted in higher total tuber yields than seedpieces planted at wider intervals (15 to 91 cm). Despite this, the total yield from the 8-cm-spacing treatment returned less dollars per ha than those from wider spacing treatments due to a high percentage of undersized tubers. They concluded that average tuber weight decreased as seedpieces were planted closer together, and vice versa. Similarly, Rupp and Thornton (1992) and Halderson et al. (1992) found an increase in the yield of small, undersized tubers (>113 g) from seedpieces that were clumped together vs those spaced farther apart.

Few studies have provided an estimate of economic loss from missing or irregularly spaced potato plants (James et al. 1973; Rupp and Thornton 1992). James et al. (1973) estimated that an 8% loss in total tuber yield due to planter skips reduced total grower revenue in New Brunswick by $1.5 million. Rupp and Thornton (1992) determined that a 10% increase or decrease in plant number from the optimum plant population reduced grower returns from 2% to 12% for Russet Burbank. Russet Norkotah, however, was not affected by the same change in plant population. They also determined that planter skips and double-clumped seedpieces typically reduced economic return compared with uniform in-row spacing.

In addition to the effects on yield and tuber size profile, changes in plant spacing may affect weed populations (Love et al. 1995), internal and external tuber defect levels (Entz and LaCroix 1984), disease incidence and severity (Firman and Allen 1995), and stem and tuber number (Love and Thompson-Johns 1999).

Previous research does not adequately address the economic impact of missing and irregularly spaced plants. Additionally, grower revenue loss from each missing or irregularly spaced potato plant has yet to be reported. The reported research was undertaken to more specifically define the agronomic and economic impact of missing plants and irregular spacing errors common to Washington potato fields.

TREATMENTS[a]

1. Optimum (optimum in-row seed spacing, R. Burbank = 31 cm, R. Norkotah = 26 cm)

Row 1	B	X	X	X	X	X	X	3-plant-unit and border rows repeated to a total	B
Row 2	B	X	X	X	X	X	X	of eight or ten consecutive 3-plant-units for each	B
Row 3	B	X	X	X	X	X	X	plot, treatment and cultivar.	B

2. Skip (planter skip)

B	X	X	X	X	X	X		B
B	X	o	X	X	o	X	repeated ...	B
B	X	X	X	X	X	X		B

3. Double (two seedpieces clumped together)

B	X	X	X	X	X	X		B
B	X	xx	X	X	xx	X	repeated…	B
B	X	X	X	X	X	X		B

4. Skip-Double (planter skip followed by two seedpieces clumped together)

B	X	X	X	X	X	X		B
B	X	o	xx	X	o	xx	repeated…	B
B	X	X	X	X	X	X		B

5. Neighbor[b] *(neighbor-row plants adjacent to a missing plant)*

B	X	X	X	X	X	X		B
B	X	X	X	X	X	X	repeated…	B
B	X	o	X	X	o	X		B

[a]X = one seedpiece, xx = two clumped seedpieces, o = no seed planted, B = border seedpieces (red potatoes), discarded at harvest.
[b]This treatment designed to determine effects of a missing plant on the neighbor-row plants.

FIGURE 1.
Three-plant-unit treatment design and seed distribution. Each box contains one three-plant-unit. Each Russet Burbank and Russet Norkotah plot contained eight and 10 consecutive three-plant-units, respectively. Data were collected from the center rows containing the three-plant-units.

MATERIALS AND METHODS

The effects of planting errors common to commercially available potato planters — planter-skips, missing plants, and clumped seedpieces — were investigated in four field experiments during 2001 and 2002. Russet Burbank (R. Burbank), an indeterminate vine-type cultivar, and Russet Norkotah (R. Norkotah), a determinate vine-type cultivar, were hand-planted into five spatial patterns. Treatments included (1) optimum spacing (optimum), (2) a simulated planter-skip/missing plant (skip), (3) two clumped seedpieces side by side (double), (4) a simulated planter-skip/missing plant followed by two clumped seedpieces (skip-double), and (5) neighbor-row plants next to a planter-skip/missing plant (neighbor) (Figure 1).

Regional standard spacing averages of 31 cm for R. Burbank and 26 cm for R. Norkotah were selected for each cultivar's optimum treatment. Treatments were planted in a three-plant-unit area design, allowing for measurement of agronomic compensation from plants surrounding each planter error (Figure 1). Seedpiece number and spacing within each three-plant unit area for R. Burbank were (1) optimum = three pieces evenly spaced at 31cm; (2) skip = two pieces at 61 cm apart; (3) double = one piece, a 31-cm space, two clumped pieces, a 31-cm space, and one piece; (4) skip followed by a double = one piece followed by a 61-cm space and two pieces clumped together, and (5) neighbor = planted same as optimum; one adjacent row contained a planting pattern similar to the skip treatment (Figure 1). Treatments were the same for R. Norkotah, but were based on an in-row spacing factor of 26 cm rather than 31 cm. Each R. Burbank three-plant-unit length totaled 91 cm and was repeated eight times within each plot (Figure 1). Each R. Norkotah three-plant-unit length totaled 76 cm and was repeated 10 times per plot (Figure 1). Plots were three rows by 7.4 m and 7.5 m for R. Burbank and R. Norkotah, respectively. Row width was 86.4 cm.

Certified seed tubers were hand-cut into pieces ranging from 57 to 85 g and hand-planted in an open furrow using the appropriate spatial arrangement. Each cultivar was planted separately in its own trial. The seedpieces were immediately covered with 20 cm of soil using tractor-pulled hilling discs. One plant of a red-skinned cultivar, Red LaSoda, guarded the end of each row and plot to provide row-end data plants with the appropriate inter-plant competition.

Plant and Tuber Information

All experiments were planted at the Washington State University Research Unit near Othello, WA, in a Shano silt loam soil on 11 April of both years and grown under regional standard practices. R. Norkotah was harvested 124 and 116 days after planting in 2001 and 2002, respectively. R. Burbank was harvested after 180 and 151 days in 2001 and 2002, respectively. Plant emergence, aboveground stem number (2002 only), and at-harvest tuber number, weight, length, width, size distribution, yield, and quality were measured. All data were collected from the center row of each plot.

Plots were harvested with a one-row mechanical plot harvester. Each tuber was washed, weighed, and counted. Total tuber yield was partitioned into U.S. No. 1 yield, market yield (U.S. No. 1 and U.S. No. 2 tubers combined), carton yield (U.S. No. 1 tubers from 199 to 510 g), and cull yield (malformed, green, and undersized (<113 g) tubers). Five 340-g to 397-g tubers from each plot were evaluated for hollow heart, internal brown spot, and brown center defects. Length-to-width ratios of five 227-g to 340-g tubers from each plot were calculated. A composite of 20 tubers weighing between 227 and 340 g was used to determine tuber specific gravity using the weight-in-air/weight-in-water method.

Economic Value

Gross income ($/three-plant-unit) minus seed expense was determined for R. Norkotah using four-year regional average fresh-market values for 1997/98 to 2000/01 market periods (Table 1) (USDA Federal-State Market News Service 1998-2001). Seed-cost-adjusted gross income for R. Burbank using regional process-market values was also determined. Process-market values were based on the criteria below, similar to that used by Washington potato processors.

1. Base price per 1000 kg was $85.11 for market-grade (U.S. No. 1 and 2) tubers.
2. Premiums for 170-g and larger market-grade tubers of $0.66/1000 kg for each percentage point greater than

TABLE 1—*Potato fresh market packaging, grade and size classifications, and four-year average shipping point prices in the Columbia Basin of Washington for market periods 1997/1998-2000/2001. Prices are listed per tuber size and grade with associated packing fees.*

Market/Packaging[a]	Grade and Tuber Size Range: U.S. No. 1[b]	Grade and Tuber Size Range: U.S. No 2	Four-Year WA State Columbia Basin Average Prices[c]	Pack-Shed Fee: Packaging and Handling	Adjusted Value[d]
	g	g	$/1000 kg	$/1000 kg	$/1000 kg
Cartons					
100 Count	199 to 241		$213.22	77.18	136.04
90 Count	242 to 269		$242.11	77.18	164.93
80 Count	270 to 298		$275.85	77.18	198.67
70 Count	299 to 354		$313.77	77.18	236.59
60 Count	355 to 397		$313.11	77.18	235.93
50 Count	398 to 510		$302.97	77.18	225.79
4.5 kg Film Bags					
Non-size A	113 to 198		$148.18	77.18	71.00
45 kg Burlap Sacks					
170 g min. size U.S. No. 2	511 to 567	170 to 567	$129.21	77.18	52.03
Bulk					
Process culls	<113	<170	$44.10	77.18	-33.08
Process culls	>567	>567	$44.10	77.18	-33.08

[a]Count = tuber number per 22.7 kg carton.
[b]511 to 567 g U.S. No. 1 tubers were priced at U.S. No. 2 170-g minimum size.
[c]Sales F.O.B. Shipping Point, market periods 1997/1998 through 2000/2001 (USDA Federal-State Market News Service 1997-2000). Forty-five kg sacks (U.S. No. 2) were priced at 50% of carton and non-size A four-year average value. Process culls priced at the 2003 regional process price.
[d]Adjusted value = Four-year average price minus pack-shed fee.

50% they contributed to the total tuber-yield composite with a maximum up to 70% or $13.23/1000 kg. Penalties were $0.66/1000 kg for each percentage point below 50%. Below 48%, penalties were $1.32/1000 kg with no rejection minimum.

3. Premiums for average tuber specific gravity values above and penalties for values below 1.077. Premium per 1000 kg was $3.31 at 1.077, $5.51 at 1.078, $7.28 at 1.079, $8.82 at 1.080, $10.58 at 1.081, $12.13 at 1.082, $13.89 at 1.083, with a maximum of $15.44 for 1.084 and above. For each 0.001-point below 1.077, tuber lots were penalized $3.31/1000 kg with no rejection minimum.
4. Undersized market-grade potatoes <113 g (process culls) were valued at $44.10/1000 kg.
5. No premiums or penalties were applied for tuber fry color, sugar content, bruise, damage, or internal defects.

Seed costs were calculated using a cut-seed cost of $264.60/1000 kg for each cultivar. An average seedpiece weight of 71 g was used in the calculation along with the appropriate seedpiece number per treatment. During the economic analysis for both cultivars, yield values from the skip treatment were used to create an additional treatment referred to as "blind/rot." The blind/rot treatment represents a situation where a plant is missing due to a blind or rotten seedpiece rather than from a planter skip. By using yield values from the skip treatment in combination with the cost of one additional seedpiece per three-plant-unit, the blind/rot economic values were calculated for each cultivar.

Economic Value to Industry

During 2000, 2001, and 2002, 70 Washington potato fields were sampled for common seedpiece spacing errors and missing plants (Pavek and Thornton 2005). This information was used in combination with the economic value of the three-plant-units to calculate the estimated loss ha^{-1} in grower revenue resulting from the planting errors. Market-specific values and losses were calculated for each cultivar. In addition, losses due only to planter skips were calculated using the minimum, maximum, and average skip numbers found in the 70-field survey. Loss in grower revenue was based on 12,663 R. Burbank and 15,196 R. Norkotah three-plant-units ha^{-1}. Only those treatments and associated values that were significantly different from the optimum spacing value were used to calculate estimated revenue loss for each cultivar.

Statistical Analysis

For each cultivar, all data were analyzed using analysis of variance and the means statistically separated using Fisher's Protected Least Significant Difference Test at the 0.05 level of probability. Within cultivar, all 2001 and 2002 data were combined for analysis.

TABLE 2—*Main effects of treatment and year on Russet Burbank stems and tubers during 2001 and 2002.*

Treatment and Year	Stem[a] No. per Plant	Stem[a] No. per 3-plant-unit[b]	Tuber No. per Plant	Tuber No. per 3-plant-unit	Tuber No. per Stem	Tuber Average Weight Mean	Tuber Average Weight Heaviest[c]	Tuber Specific Gravity
						g	g	
Optimum	2.2 ab[d]	6.5 b	10.0 b	30.0 b	4.6	201 bc	763 b	1.0802
Neighbor	2.0 b	5.9 b	9.9 b	29.6 b	5.0	207 b	856 ab	1.0789
Double	1.9 b	7.6 a	8.4 c	33.8 a	4.5	190 c	794 b	1.0790
Skip	2.4 a	4.7 c	11.9 a	23.9 c	5.0	233 a	919 a	1.0797
Skip-Double	2.1 ab	6.2 b	9.6 b	28.7 b	4.6	204 b	782 b	1.0798
(p-Value)	0.0462	0.0005	0.0001	0.0001	NS	0.0001	0.0339	NS
2001			10.02	29.38		187 b	26.9	1.0816 a
2002			9.91	29.01		227 a	31.1	1.0776 b
(p-Value)			NS	NS		0.0001	NS	0.0099

[a]Above-ground stem counts, taken in 2002 only.
[b]See Figure 1 for three-plant-unit definition and design.
[c]Heaviest tuber from each plot and treatment averaged across replications.
[d]Within each main effect, means in a column followed by the same letter are not significantly different by Fisher's Protected LSD Test at the 0.05 level.

TABLE 3—*Main effects of treatment and year on Russet Norkotah stems and tubers during 2001 and 2002.*

Treatment and Year	Stem[a] No. per Plant	Stem[a] No. per 3-plant-unit[b]	Tuber No. per Plant	Tuber No. per 3-plant-unit	Tuber No. per Stem	Tuber Average Weight Mean	Tuber Average Weight Heaviest[c]	Tuber Specific Gravity
						g	g	
Optimum	1.9 b[d]	5.8 b	5.8 b	17.5 b	3.0	210 ab	709 b	1.0736
Neighbor	2.0 b	6.0 b	5.8 b	17.5 b	2.9	208 ab	793 ab	1.0736
Double	1.9 b	7.6 a	4.9 c	19.6 a	2.6	194 b	685 b	1.0724
Skip	2.4 a	4.8 c	6.9 a	14.1 d	2.9	223 a	855 a	1.0729
Skip-Double	1.9 b	5.6 bc	5.4 b	16.2 c	2.9	208 ab	853 a	1.0746
(p-Value)	0.0026	0.0001	0.0001	0.0001	NS	0.0200	0.0365	NS
2001			6.0 a	17.8 a		234 a	913 a	1.0725
2002			5.5 b	16.1 b		183 b	650 b	1.0743
(p-Value)			0.0320	0.0074		0.0001	0.0009	NS

[a]Above-ground stem counts, taken in 2002 only.
[b]See Figure 1 for 3-plant-unit definition and design.
[c]Heaviest tuber from each plot and treatment averaged across replications.
[d]Within each main effect, means in a column followed by the same letter are not significantly different by Fisher's Protected LSD Test at the 0.05 level.

TABLE 4—*Russet Burbank yield by category and size. Years 2001-2002 combined.*

Treatment and Year	Total Yield	Total Yield of Tubers <113 g	Total Yield of Tubers >397 g	Total Market[a] Yield	Market Yield >170 g	U.S. No. 1[a] Yield	Culled Tuber Yield[c] Malformed	Culled Tuber Yield[c] Green
	kg/3-plant-unit[d]				% of total yield	kg/3-plant-unit		
Optimum	6.1 ab[c]	0.61 b	1.3 bc	5.3 a	75 b	4.6 a	0.22	0.10 c
Neighbor	6.1 ab	0.64 b	1.6 ab	5.1 ab	74 b	4.3 ab	0.24	0.15 abc
Double	6.4 a	0.81 a	1.1 c	5.2 a	70 c	4.4 a	0.32	0.11 bc
Skip	5.5 c	0.45 c	1.8 a	4.6 c	79 a	3.5 c	0.37	0.19 a
Skip-Double	5.8 b	0.61 b	1.4 bc	4.8 bc	74 b	3.9 b	0.32	0.17 ab
(p-Value)	0.0001	0.0001	0.0057	0.0007	0.0001	0.0001	NS	0.0347
2001	5.5 b	0.71 a	0.9 b	4.3 b	79 a	3.3 b	0.41 a	0.11
2002	6.5 a	0.54 b	1.9 a	5.6 a	69 b	4.9 a	0.18 b	0.17
(p-Value)	0.0023	0.0002	0.0001	0.0002	0.0001	0.0001	0.0019	NS

[a]Market yield (U.S. No. 1 and 2 grade tubers); U.S. No. 1 yields are comprised of tubers >113 g.
[b]See Figure 1 for three-plant-unit definition and design.
[c]Within each main effect, means in a column followed by the same letter are not significantly different by Fisher's Protected LSD Test at the 0.05 level.

RESULTS

In all data categories, treatments performed similarly each year and no year-by-treatment interactions were observed. Plant emergence averaged across years and treatments was 99.8% and 99.5% within the R. Burbank and R. Norkotah trials, respectively.

Stem and Tuber Values

Optimum, neighbor, and skip-double treatment plants produced similar stem and tuber numbers per plant within each cultivar (Tables 2 and 3). The largest differences in tuber and stem number were seen between the double and skip treatments. In-row R. Burbank plants on each side of a skip produced 2.4 stems and 11.9 tubers compared with double treatment plants, which averaged 1.9 stems and 8.4 tubers per plant. R. Norkotah double treatment plants averaged 1.9 stems and 4.9 tubers per plant, and skips averaged 2.4 stems and 6.9 tubers per plant.

Stem number was similar between the double and optimum treatments for each cultivar, yet the double treatment produced significantly fewer tubers per plant (Tables 2 and 3).

TABLE 5—*Russet Norkotah yield by category and size. Years 2001 and 2002 combined.*

Treatment and Year	Total Yield	Total Yield of Tubers <113 g	Total Yield of Tubers >397 g	Market[a] Yield	U.S. No. 1[a] Yield	Carton[b] Yield	Carton Yield as a % of Total Yield	Culled Tuber Yield[c] Malformed	Culled Tuber Yield[c] Green
	kg/3-plant-unit[d]						%	kg/3-plant-unit	
Optimum	3.7 a[e]	0.35 bc	0.90	3.2 a	2.9 a	1.9 a	50.7 a	0.01 b	0.06 b
Neighbor	3.6 ab	0.38 b	0.84	3.1 ab	2.8 a	1.8 a	50.3 ab	0.02 b	0.12 ab
Double	3.8 a	0.44 a	0.76	3.2 a	2.8 a	1.7 ab	43.7 c	0.01 b	0.07 b
Skip	3.2 c	0.27 d	0.91	2.7 c	2.4 b	1.6 b	49.6 ab	0.05 a	0.17 a
Skip-Double	3.4 bc	0.33 c	0.88	2.9 bc	2.5 b	1.6 b	46.4 bc	0.03 ab	0.13 ab
(p-Value)	0.0001	0.0001	NS	0.0024	0.0002	0.0004	0.0053	0.0300	0.0500
2001	4.2 a	0.33 b	1.33 a	3.5 a	3.0 a	2.0 a	47.2		
2002	2.9 b	0.38 a	0.39 b	2.6 b	2.4 b	3.2 b	48.9		
(p-Value)	0.0001	0.0040	0.0001	0.0001	0.0001	0.0002	NS		

[a]Market yield (U.S. No. 1 and 2 grade tubers) and U.S. No. 1 yields are comprised of tubers >113 g.
[b]Carton yield is comprised of U.S. No. 1 grade tubers weighing between 199 and 510 g.
[c]Malformed and green yields represent 2002 only as these two categories were not separated in 2001.
[d]See Figure 1 for three-plant-unit definition and design.
[e]Within each main effect, means in a column followed by the same letter are not significantly different by Fisher's Protected LSD Test at the 0.05 level.

The R. Norkotah skip treatment produced more stems per plant than the other R. Norkotah treatments (Table 3).

Average Tuber Weight

Despite having the highest tuber number per plant, the skip treatment of R. Burbank produced the highest average tuber weight (Table 2). In addition, both the skip and neighbor treatments produced tubers with some of the heaviest individual weights (Table 2). For R. Norkotah, average tuber weight was similar among the optimum, neighbor, skip, and skip-double treatments (Table 3). With the exception of the skip treatment, the average tuber weights for all treatments were not different than that of the double treatment. The skip, skip-double, and neighbor R. Norkotah treatments produced tubers with the heaviest individual weights (Table 3). For both cultivars, the densely planted double treatments produced lower average tuber weights than the skip treatments (Tables 2 and 3).

Tuber Quality, Size Distribution, and Yield

Treatments did not affect the length-to-width ratio (data not shown) or tuber specific gravity for either cultivar (Tables 2 and 3). No treatment or year effects were seen for internal defects (data not shown).

The R. Burbank skip treatment produced more green tubers than the optimum treatment; malformed tuber yield was not affected (Table 4). The same was true for R. Norkotah with the exception that the skip treatment also produced more malformed tubers than the optimum treatment (Table 5). The skip, skip-double, and neighbor treatments for both cultivars produced similar green tuber yields (Tables 4 and 5).

Plant density and in-row spacing affected tuber size distribution and yield. Total yield for the double treatment was among the highest for both cultivars, but this treatment also produced the highest yield of undersized (<113 g) tubers (Tables 4 and 5). The skip treatment of both cultivars produced the lowest yield of undersized tubers (Tables 4 and 5) and for R. Burbank, the highest proportion of large (>397 g) tubers (Table 4). Each R. Burbank plant in the skip treatment yielded 2.75 kg (5.5 kg / 2 plants) in total yield while each plant in the optimum treatment yielded only 2.03 kg (6.1 kg / 3 plants) (Table 4). The additional 0.72 kg of total yield from each plant surrounding the skip allowed for 71% [(0.72 kg x 2 plants / 2.03 kg) x 100] compensation of the missing plant's yield. Similarly, R. Norkotah plants in the skip treatment compensated for 60% of the missing plants total yield (Table 5). Despite compensation by the in-row neighbor plants, the skip treatment of both cultivars produced the lowest total, market,

TABLE 6—*Russet Burbank process market values for each treatment. Years 2001 and 2002 combined.*

Treatment and Year	Treatment Value[a] 3-plant-unit[c]	Plant	% of Opt. Treatment Value[b] 3-plant-unit[c]	Plant
	$	$	%	%
Optimum	0.53 a[e]	0.18 b		
Neighbor	0.50 ab	0.17 bc	95	95
Double	0.50 ab	0.13 e	95	71
Skip	0.46 c	0.23 a	87	131
Skip-Double	0.47 bc	0.16 cd	89	89
Blind/Rot[d]	0.44 c	0.22 a	84	126
(p-Value)	0.0004	0.0001		
2001	0.42 b	0.16 b		
2002	0.54 a	0.20 a		
(p-Value)	0.0002	0.0001		

[a]Grower-paid gross income, value per unit or plant, less seed expense.
[b]Values rounded.
[c]See Figure 1 for three-plant-unit definition and design.
[d]The blind/rot treatment was derived using the yield values from the skip treatment. The only difference between the two treatments is the seed expense.
[e]Within treatment or year, means in a column followed by the same letter are not significantly different by Fisher's Protected LSD Test at the 0.05 level.

TABLE 7—*Russet Norkotah fresh market values for each treatment. Years 2001 and 2002 combined.*

Treatment and Year	Treatment Value[a] 3-plant-unit[c]	Plant	% of Opt. Treatment Value[b] 3-plant-unit[c]	Plant
	$	$	%	%
Optimum	0.37 a[e]	0.12 b		
Neighbor	0.37 a	0.12 b	98	98
Double	0.32 b	0.08 d	85	64
Skip	0.32 b	0.16 a	86	129
Skip-Double	0.31 b	0.10 c	82	82
Blind/Rot[d]	0.30 b	0.15 a	81	122
(p-Value)	0.0103	0.0001		
2001	0.38 a	0.14 a		
2002	0.27 b	0.10 b		
(p-Value)	0.0004	0.0013		

[a]Grower-paid gross income, value per unit or plant, less seed expense.
[b]Values rounded.
[c]See Figure 1 for three-plant-unit definition and design.
[d]The blind/rot treatment was derived using the yield values from the skip treatment. The only difference between the two treatments is the seed expense.
[e]Within treatment or year, means in a column followed by the same letter are not significantly different by Fisher's Protected LSD Test at the 0.05 level.

and U.S. No. 1 yields of all treatments, with the exception of the skip-double treatment (Tables 4 and 5). The skip-double treatment yields were often similar to those of the skip treatment.

For the process market, the most valuable tubers were those >170 g. Seventy-nine percent of the R. Burbank skip treatment's total yield was comprised of market-grade tubers >170 g, which was significantly higher than all other R. Burbank treatments (Table 4). Seventy-five percent of the R. Burbank optimum treatment total yield was market grade tubers >170 g, which was not significantly different from the skip-double and neighbor treatments at 74%. At 70%, the R. Burbank double treatment had the lowest proportion of >170-g market-grade tubers.

For both cultivars, the optimum, neighbor, and double treatments had similar total, market, and U.S. No. 1 yields (Tables 4 and 5). In addition, these same treatments for R. Norkotah had similar carton yields (Table 5). Despite the similarities, the total yield of the R. Norkotah double and skip-double treatments produced the lowest proportions of carton-grade tubers. Nearly 50% of the R. Norkotah total yield from the optimum, neighbor, and skip treatments was of carton grade compared with less than 47% for the double and skip-double treatments (Table 5).

Economic Values

The three-plant-unit values of the optimum spacing treatment were consistently among the highest for both cultivars. Three optimally spaced plants were valued at $0.53 for R. Burbank on the process market (Table 6) and $0.37 for R. Norkotah on the fresh market (Table 7).

Under optimum spacing, each R. Burbank plant was valued at $0.18 compared with each plant in the skip treatment, which was valued at $0.23 (Table 6). The additional value of each skip treatment plant came primarily from an increase in yield that was likely due to the lack of in-row competition. This $0.05 gain from each plant resulted in a compensation of 56% [($0.05 x 2 plants / $0.18) x 100] of the missing plant's value. Collectively, all plants from the R. Burbank skip treatment returned 87% of the economic value of those in the optimum treatment (Table 6). R. Norkotah's fresh market value under optimum spacing was $0.12 plant^{-1} while each plant in the skip treatment was valued at $0.16 (Table 7). The additional $0.04 from each skip treatment plant resulted in a compensation of 67% of the missing R. Norkotah plant's economic value. Similar to R. Burbank, plants from the R. Norkotah skip treatment collectively returned 86% of the value of those in the optimum treatment (Table 7). Plants of either cultivar in the row adjacent (neighbor treatment) to a skip failed to compensate economically for their missing neighbor (Tables 6 and 7).

Individual plants of the double treatment for both cultivars were less valuable than plants of other treatments (Tables 6 and 7). Under process market values, however, the R. Burbank double treatment produced a three-plant-unit value similar to that of optimum spacing. Clumped seedpieces (doubles) reduced the fresh market three-plant-unit value by 15% for R. Norkotah relative to the optimum spacing (Table 7). For both cultivars, the skip-double and blind/rot individual and three-plant-unit values were significantly lower than those of the optimum treatment (Tables 6 and 7).

Economic Importance to Industry

From the 70 Washington potato fields sampled during 2000 through 2002, an average of 2700 planter skips, 250 blind or rotten seedpieces, and 1980 double-clumped seedpieces ha^{-1} was recorded (Pavek and Thornton 2005). Of the 2700 planter skips ha^{-1}, 500 were followed by double clumps similar to the skip-double treatment.

R. Burbank growers with plant populations similar to the 70-field average from Washington may be losing 4.4 % of their seed-cost-adjusted gross income (Table 8), while R. Norkotah growers may be losing an estimated 2.9% (Table 9). Losses to the grower for R. Burbank were estimated at \$200 ha^{-1} for potatoes sold to a processor (Table 8). On the fresh market, the estimated loss for R. Norkotah using the 70-field average was \$250 ha^{-1} (Table 9).

The largest revenue loss for both cultivars came from planter-skip-related errors. Using the 70-field average, skips alone accounted for a loss of 2.5% or more of adjusted gross income for both cultivars (Table 10). The field with the highest number of skips (11,000 ha^{-1}) would have an adjusted gross income loss for R. Burbank of up to 11.1%, or \$740 ha^{-1}, vs a field with no skips (optimum spacing). For the same field, losses to a R. Norkotah grower would have been 10.2% of adjusted gross income (Table 10).

DISCUSSION

Missing plants, blind and rotten seedpieces, and irregular in-row spacing are costly to Washington potato growers; and presumably, to all potato growers. Growers lose money because these stand-establishment issues typically change tuber size profile and reduce yield. Planter skips alone are costing Washington growers as much as 11.1% of their seed-cost-adjusted gross income. Growers with plant populations similar to the 2000-2002 survey may have lost anywhere from

TABLE 8—*Process market: estimated cost of missing and irregularly spaced Russet Burbank plants to Washington State potato growers with a plant population similar to the average of a 70-field survey conducted in Washington (Pavek and Thornton 2005).*

	Adjusted Gross Income[a]	
R. Burbank—Spatial Arrangement	\$/ha	%
Optimum spacing	6,700	100.0
	Difference from Optimum Spacing	
70-Field Ave., Error[b] Frequency/ha		
2,200 planter skips	-150	-2.2
500 skips followed by doubles	-30	-0.4
250 blind or rotten seedpieces	-20	-0.3
Potential Grower Loss:	-200	-2.9

[a]Gross income from process market, less seed expense. Optimum spacing value based on 12,663 3-plant-units ha^{-1}. Most values have been rounded.
[b]Only those errors and associated values that were significantly different from the optimum spacing value were included in this table.

TABLE 9—*Fresh market: estimated cost of missing and irregularly spaced Russet Norkotah plants to Washington State potato growers with a plant population similar to the average of a 70-field survey conducted in Washington (Pavek and Thornton 2005).*

	Adjusted Gross Income[a]	
R. Norkotah—Spatial Arrangement	\$/ha	%
Optimum spacing	5,670	100.0
	Difference from Optimum Spacing	
70-Field Ave., Error[b] Frequency/ha		
2,200 planter skips	-115	-2.0
500 skips followed by doubles	-34	-0.6
1,480 doubles	-85	-1.5
250 blind or rotten seedpieces	-17	-0.3
Potential Grower Loss:	-250	-4.4

[a]Gross income from fresh market, less seed expense. Optimum spacing value based on 15,196 3-plant-units ha^{-1}. Most values have been rounded.
[b]Only those errors and associated values that were significantly different from the optimum spacing value were included in this table.

Table 10—*Estimated cost of planter skips to Washington potato growers for Russet Burbank and Russet Norkotah sold to a fresh-pack operation or processor. Skip values obtained from a 70-field survey conducted in Washington during 2000-2002 (Pavek and Thornton 2005).*

	Difference from Optimum Spacing Adjusted Gross Income[a]					
	Least Skips/Field		Most Skips/Field		70-Field Mean	
Market/Cultivar	(370 skips/ha)		(11,000 skips/ha)		(2,700 skips/ha)	
Fresh Market:	$/ha	%	$/ha	%	$/ha	%
R. Norkotah	-20	-0.3	-575	-10.2	-140	-2.5
Process Market:						
R. Burbank	-25	-0.4	-740	-11.1	-180	-2.7

[a]Gross income, less seed expense.

2.9% to 4.4% of their potential gross return. Put differently, planter skips and non-uniform in-row spacing may have cost Washington growers between $13.8 and $17.3 million across the 69,000 ha of potatoes they planted in 2002. Individual growers may have realized an economic loss somewhere between $10,000 and $13,000 for each average-sized center-pivot irrigated field (50.6 ha).

Contrary to studies conducted in different growing regions (Pascal et al. 1977; Entz and LaCroix 1984; Sieczka 1986), irregular in-row spacing can result in yield loss, especially in the Columbia Basin of Washington where potato yields are much higher. Conceivably, the higher yields of the Columbia Basin serve to amplify small yield differences, which might otherwise be obscured in the residual error of the experiments conducted in regions with lower yields. Although the tuber yield and size profile of R. Burbank and R. Norkotah were both affected by irregular plant spacing, one should consider the possibility that other varieties might respond differently, regardless of the growing region.

The treatment simulating a planter skip resulted in the lowest total and market yields of all treatments for each cultivar, despite the fact that in-row plants next to the simulated skip compensated for 60% to 71% of their missing neighbor's yield. In addition, no yield compensation was seen from plants in the row adjacent to the simulated planter skip. Similar to findings of Hide et al. (1996), the lack of competition due to the missing plant benefited the growth of in-row neighbor plants but failed to benefit the growth of adjacent-row neighbor plants. When potatoes are planted into 86-cm-wide rows, it appears that at least some varieties in the Columbia Basin of Washington have sufficient room for side growth (across the row) and are therefore less affected by slight changes in row-to-row competition.

In addition to yield loss, non-uniform plant spacing and gaps from missing plants influence stem and tuber numbers, average tuber weight, external tuber defects, tuber greening, and tuber size distribution of surrounding plants. Comparison between the skip and double treatments revealed that both cultivars produced more stems and tubers per plant, in addition to larger tubers, as the plant population was reduced and in-row plants spaced farther apart. This growth response parallels findings from Russet-type cultivars in a seedpiece-spacing study by Love and Thompson-Johns (1999) in Idaho.

Planter skips and missing plants also contribute to an increase in external tuber malformation and in-field tuber greening. The R. Norkotah skip treatment produced the highest yield of malformed tubers of all R. Norkotah treatments. For both R. Norkotah and R. Burbank, the treatments with missing plants (skip, skip-double, and neighbor) had the highest green-tuber yields. It is reasonable to assume that the lack of canopy shading due to missing plants, and the resulting increase in sunlight to the soil surface, contributed to tuber greening during the growing season. Additionally, larger tubers produced as a result of reduced plant-to-plant competition in the skip and skip-double (R. Norkotah only) treatments likely crowded the hill and push themselves or other tubers out of the hill.

The right combination of plant population and spatial arrangement is essential for growers to optimize tuber size profile, and in turn, revenue. Going either direction from the optimum combination can result in financial loss. The importance of plant population was demonstrated by the optimum plant population treatments producing higher yields and economic values compared with the reduced plant population of the planter-skip treatment. The difference was two vs three plants in the same unit area. Increasing the population beyond optimum, however, also leads to revenue loss. The four plants of the double treatment were less valuable, under fresh market analysis for R. Norkotah, than three plants in the optimum treatment. Although yields were similar between the double and optimum treatments, the double treatment produced fewer market-sized tubers and more of the lower-valued, undersized (<113 g) tubers.

Without proper spatial arrangement, plant population by itself is of marginal importance in optimizing economic return. As an example, the treatments that had the optimum and skip-double plant spacing had identical plant populations, yet the uniformly spaced optimum treatment produced higher yields and economic value for both cultivars.

For process market R. Burbank growers, planter skips and missing plants are more costly ($) than double clumped seedpieces. Fresh market R. Norkotah growers should expect similar losses from both missing plants and double-clumped seedpieces. Ultimately, the tuber size profile requirements of the intended market will dictate the value of potatoes coming from a non-uniform stand. Uniform plant populations with ideal in-row spacing appear to be more crucial for fresh market potatoes; the process market tends to be more forgiving due to broader tuber size profile requirements. Regardless of the market, however, yield losses from less-than-optimum stands will affect grower revenue.

Twenty-one percent of the fields surveyed in Washington between 2000 and 2002 contained at least 700 planter skips ha^{-1} where three or more consecutive plants were missing (Pavek and Thornton 2005). Because the skip treatment from the reported study simulated only a single planter skip (one missing plant), the revenue loss in Washington fields may actually be higher than the estimated \$200 to \$250 ha^{-1}. Stewart (1921) determined that when three consecutive plants were missing, the in-row plants on either side of the missing plant area compensated 87% in yield for only one of the missing plants. The potential productivity of the other two plants was completely lost.

With current planter technology and management, desired plant population and spacing in Washington are typically not achieved. More accurate seedpiece placement would likely come from new planter technology and better management. Based on technological advances in other farming equipment, it is likely that new planter technology will bring improvements to future potato populations. Because premiums are often paid for tubers of uniform shape and size, growers must strive for uniformly spaced plant populations that will provide them with the highest economic return. Until new technology is available, growers need to manage seed-cutting operations and planting operations to optimize plant populations, spatial arrangement, and, in turn, profit.

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