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Effects of In-Row Spacing on Yield, Tuber Size Profiles, Bruise Damage, and Crop Values for Cultivars Alturas, Clearwater Russet and Ranger Russet in the Columbia Basin

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Abstract

Variety selection and cultural management practices are the most common considerations for improved profitability in potato production systems. Planting density investigations have led to both within and between-row spacing recommendations to maximize profitability for commonly grown potato cultivars. Planting density can significantly alter tuber set, tuber size distribution, yield and profitability depending on end-use of the crop. However, rarely have such investigations included an assessment of the residual effects of changes in tuber size distribution on tuber bruising (blackspot and shatter bruise) and associated financial returns. The physics of impact injury suggests that larger tubers are more prone to tuber bruising than smaller tubers when dropped from a similar height. In this study we varied the in-row spacing of seed to investigate the extent to which the associated changes in tuber size distribution affect tuber bruising and crop values. The results demonstrated that: (1) the extent of tuber bruising was directly correlated with total marketable yield as altered by in-row spacing; (2) marketable yields decreased as in-row spacing increased; (3) while the absolute yield (MT ha^{-1}) of bruised tubers increased with closer in-row spacing, the spacing-induced shifts in tuber size distribution had no effect on the *percentage* of bruised tubers as a proportion of total yield; (4) larger tubers were more prone to bruising; and (5) closer in-row spacing significantly improved financial returns for both processing and seed contracts despite the increase in bruise yield.

Resumen

La selección de variedades y las prácticas de manejo cultural son las consideraciones más comunes para mejorar la rentabilidad en los sistemas de producción de papa. Las investigaciones sobre la densidad de siembra han dado lugar a recomendaciones de espaciamiento tanto dentro como entre hileras para maximizar la rentabilidad de las variedades de papa comúnmente cultivadas. La densidad de siembra puede alterar significativamente la tuberización, la distribución del tamaño de los tubérculos, el rendimiento y la rentabilidad en función del uso final del cultivo. Sin embargo, rara vez estas investigaciones han incluido una evaluación de los efectos residuales de los cambios en la distribución del tamaño de los tubérculos sobre los golpes de los tubérculos (manchas negras y hematomas por rotura) y los rendimientos financieros asociados. La física de las lesiones por impacto sugiere que los tubérculos más grandes son más propensos a magulladuras que los tubérculos más pequeños cuando se dejan caer desde una altura similar. En este estudio, variamos el espaciamiento de las semillas en las hileras para investigar hasta qué punto los cambios asociados en la distribución del tamaño de los tubérculos afectan la magulladura de los tubérculos y los valores del cultivo. Los resultados demostraron que: (1) el grado de magulladuras de los tubérculos se correlacionó directamente con el rendimiento total comercializable alterado por el espaciamiento dentro de las hileras; (2) los rendimientos comercializables disminuyeron a medida que aumentó el espaciamiento entre hileras; (3) mientras que el rendimiento absoluto (MT ha^{-1}) de los tubérculos afectados aumentó con el espaciamiento más estrecho en

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las hileras, los cambios inducidos por el espaciamiento en la distribución del tamaño de los tubérculos no tuvieron ningún efecto sobre el porcentaje de tubérculos dañados como proporción del rendimiento total; (4) los tubérculos más grandes eran más propensos a los moretones; y (5) un espaciamiento más estrecho en los surcos mejoró significativamente los rendimientos financieros tanto para el procesamiento como para producción de semilla, a pesar del aumento en el rendimiento de los dañados.

Keywords Clearwater Russet · Ranger Russet · Alturas · Bruise · Tuber size distribution · Plant spacing · Crop value

Introduction

Total potato production in the United States in 2022 was estimated at 362,437 hectares and 17,791,829 tonnes (49.1 MT ha^{-1}). The Pacific Northwest (Idaho, Washington, Oregon) accounted for 54.9% of this acreage and 60.2% the total production, respectively (USDA-NASS 2023a & 2023b). Washington produces an estimated 23.0% of national production (USDA-NASS 2023a). Potatoes had an estimated farm-gate value of $5 billion nationally (USDA-NASS 2023b) with $1.16 billion produced in Washington. This value is market driven with most Washington potatoes destined for the frozen-processing (primarily French fry) market in the Columbia Basin.

Cultivar selection and optimization of cultural practices are critical to maximizing financial returns (Love and Thompson-Johns 1999). Processing contracts include premiums and penalties for various parameters, including grade (percent U.S. No. 1's), favorable tuber size distribution (e.g. > 170 g per tuber), disease and defect-free tubers (e.g. bruise free), and ideal chemical maturity (high specific gravity and low reducing sugars). Potato grade has been important historically because it defines the physical and visual quality of the tubers with U.S. No. 1's being defined as "well shaped" and U.S. No. 2's defined as "not seriously misshapen", but both require tubers to be clean, firm, and free from other defects and damage (USDA 2011). Common processing cultivars other than Russet Burbank include Ranger Russet, Alturas, and Clearwater Russet.

Ranger Russet (Pavek et al. 1992), Alturas (Novy et al. 2003) and Clearwater Russet (Novy et al. 2010) were released from the Pacific Northwest Potato Variety (Tri-State) Development Program in 1991, 2002, and 2008, respectively. Ranger Russet produces a higher U.S. No. 1 yield than Russet Burbank (Gonzalez et al. 2024; Blauer et al. 2024; Spear et al. 2021). Tubers of this cultivar have high specific gravity with low reducing sugars at harvest (Baley et al. 2023), an acceptable tuber shape, light fry color following 8 weeks of storage at 7.2 °C (Whitworth et al. 2016), moderate susceptibility to shatter bruise, and high susceptibility to blackspot bruise (Thornton et al. 2020).

Alturas tubers have high specific gravity and low reducing sugars at harvest, which are ideal traits for both processing and culinary fresh pack (Novy et al. 2003). It produced higher total yields in California, Colorado, Idaho, New Mexico, Oregon, and Washington than Ranger Russet and Russet Burbank. An estimated 77% of the total yield of Alturas grades as U.S. No. 1 tubers. Additionally, the tuber size profile of Alturas is comparable to Ranger Russet, and it produces acceptable fry color following 3 months of storage at 7.2 °C. Alturas has a similar susceptibility to shatter bruise as Ranger Russet, while its blackspot bruise susceptibility is equivalent to Russet Burbank (Novy et al. 2003).

Clearwater Russet is well suited for the fresh pack and processing markets due to its consistent shape, russeted skin, cold sweetening resistant phenotype, excellent out-of-storage fry color, and resistance to tuber defects such as blackspot bruise (Novy et al. 2010). During its development, Clearwater Russet produced equivalent total yields to Russet Burbank and Ranger Russet in Idaho, Oregon, and Washington trials, but higher U.S. No. 1 yield when averaged across trial locations (Novy et al. 2010).

Previous studies have highlighted the importance of in-row seed spacing for maximizing tuber yield. Knowles and Knowles (2016) showed that Ranger Russet had a higher marketable yield at 15 cm in-row spacing versus 25 and 35 cm, accounting for 110, 102, and 94 MT ha^{-1}, respectively, in Washington state. Their results demonstrated that 15 cm in-row spacing optimized returns and total yield by shifting the tuber size distribution toward 170–284 g tubers. Similar findings were reported by Love and Thompson-Johns (1999) in Idaho for Russet Burbank, Frontier Russet, and Ranger Russet, with 8 cm in-row spacing producing the highest yields, while moderate in-row spacing (23 to 46 cm) proved optimal for net returns.

In-row spacing studies lead to recommendations for the best use of spatial resources to maximize financial returns and spur further research to improve planter efficiency. Pavek and Thornton (2006) evaluated the impact of planting skips for Russet Burbank and Russet Norkotah and observed that in-row spacing at 31 and 26 cm produced the highest financial returns. Planting skips increased individual plant spacing, reduced the plant population, increased the number of tubers per plant, increased the average tuber size, and decreased the total yield. Double plantings reduced plant spacing, increased the plant population, decreased the number of tubers per plant, decreased the average tuber size, and increased the total yield. Their studies underscore the importance of consistent in-row spacing to optimize yield and grade for maximum returns.

Research on Clearwater Russet in Washington and Idaho demonstrated that total yield was greatest with closer in-row spacing, though financial returns were optimized at wider spacing when nitrogen input costs were considered. Bolding (2017) in Washington compared in-row spacings of 20, 25.4, 30.5, 35.5, and 40.6 cm and found that 20 cm produced the highest total and marketable yields (U.S. No. 1 + No. 2 yields), while 30.5 to 40.6 cm produced a higher percentage of > 170 g tubers, with 30.5-cm spacing resulting in the largest numerical 'adjusted gross return' after factoring in nitrogen fertilizer costs. Similarly, when Clearwater Russet was grown in southern Idaho, 25 cm in-row spacing produced the highest total yield, but 33 cm spacing produced the highest percent U.S. No. 1 yield (85.7% vs 82.7%) and after adjusting for nitrogen fertilizer costs, 33 cm in-row spacing produced the greatest financial return (Hatch 2017). While these studies included nitrogen input costs, neither considered how the changes in tuber size profiles with plant population may have affected bruise damage and associated crop values.

Information on the effects of in-row spacing on yield and financial return (esp. in Washington) for Alturas is limited. One study in Idaho showed that when Alturas, Russet Norkotah, and Ranger Russet were averaged for yield, closer in-row spacing (20 cm) produced the highest total yield and the highest U.S. No. 1 yield independent of seed piece size (Bohl et al. 2011).

Bruising negatively affects crop value and integrity by creating tissue damage and dark color formation. Furthermore, bruising can occur during harvest and handling (blackspot and/or shatter bruise), or during storage (pressure bruise). Blackspot bruising arises from mechanical impact on hard surfaces which results in tissue damage (Hyde et al 1996; Baritelle and Hyde 1999; Gancarz 2016). In response to impact injury, black discoloration develops in the cortical tissue underlying the periderm due to oxidation of phenolic compounds and the formation of melanin (Baritelle and Hyde 1999). Shatter bruise is described as failure of the cell wall during mechanical impact, which creates fissures in the tuber surface (Hyde et al 1996; Baritelle and Hyde 1999). These cracks provide entry points for fungal and bacterial pathogens, resulting in increased tuber decay (Franc 1996; Thornton and Bohl 1998) and crop loss.

Bruise acceptance can vary depending on the product end use, but blackspot and shatter bruise directly affect crop value through the premiums and penalties in contracts for bruise (Thornton and Bohl 1998). Moreover, bruising results in increased trim loss, handling costs, shrinkage, disease occurrence, reduced visual appeal, and diminished overall quality with an estimated financial loss of approximately U.S.$298 million annually (Brooke 1996; Thornton and Bohl 1998), and when adjusted for inflation in 2024 (Webster, CPI Inflation Calculator; www.officialdata.org), would represent a value of U.S.$597,319,931, assuming all other variables remained constant.

Efforts to mitigate tuber bruising have focused on breeding for resistance and modification of harvest and handling practices, with harvest activities contributing the most to tuber damage (Thornton and Bohl 1998, Gancarz 2016, Novy et al. 2003 & 2010). For example, Clearwater Russet's susceptibility to shatter bruise was equivalent to Russet Burbank but it was more resistant to blackspot bruise than Ranger Russet (Novy et al. 2010). Additionally, Alturas had similar shatter bruise susceptibility and better blackspot bruise resistance than Ranger Russet tubers when grown in Idaho (Novy, et al. 2003).

The extent to which bruise damage is affected by plant spacing-induced changes in tuber size distribution is largely unknown and represents a potential management opportunity to maximize financial returns. Accordingly, we modeled how in-row spacing affects yields and tuber size distributions to alter the extent of shatter and blackspot bruising for Ranger Russet, Clearwater Russet, and Alturas in the Columbia Basin of Washington. Our results highlight the significance of genetics (i.e. breeding and cultivar selection) to limit bruise damage and underscore the benefits of closer in-row spacing for higher marketable and U.S. No. 1 yields, smaller average tuber size profiles, and higher financial returns in direct comparison of spacing treatments.

Materials and Methods

Seed

Certified G3 seed (*cvs*. Ranger Russet, Clearwater Russet, and Alturas) was purchased from a commercial seed grower in Reardon, WA in March of each study year. The seed was stored at 4 °C (≥ 95% RH) until hand cutting into 50- to 64-g seed pieces. The cut seed was blocked for tuber portion (apical vs basal) and wound healed (12 °C; ≥ 95% RH) for three days prior to planting in April.

Field Plot Design and Productivity Evaluations

Seed was planted April 19, 2021, and April 20, 2022, at the Washington State University Irrigated Agriculture Research and Extension Center in Othello, WA (46°47′34.4328″ N. Lat., 119°2′19.284″ W. Long.) using a custom-built two-row assist-feed planter. Seed was planted 20 cm deep in a Shano silt loam soil (Lenfesty 1967) at 20, 28, 36, or 43-cm in-row spacing. Rows were spaced 81 cm apart on center. Five field replicates per treatment were planted with individual plots being 6.1 m in length, resulting in 15, 18, 22, or 31 plants per plot depending on the in-row spacing treatment. A guard seedpiece of cv Chieftain was planted at the beginning and end of each plot to facilitate plot separation during harvesting. Treatment plots were flanked by guard rows of Ranger Russet at 28-cm in-row spacing. Replicated plots were arranged in a randomized complete block design under a center pivot and soil moisture was maintained at a minimum of 65% field capacity as determined by soil moisture sensors. Integrated pest management and fertility (both pre-plant and in-season) were maintained using standard recommendations for late-season russet cultivars in the Columbia Basin.

Above-ground stems were counted each year just prior to row closure. The crop growth duration was 147 days from planting (DAP) to vine kill in both years. This duration was chosen because it approximates the average DAP needed for tubers of all three cultivars to achieve physiological maturity (maximum specific gravity and minimum sucrose and reducing sugar concentrations; Wohleb et al. 2014) with the full-season management practices used at the WSU Othello Research Station (Ellis et al. 2020; Knowles et al. 2008, 2019). Vine kill was accomplished using a mechanical flail vine mower. Following vine kill, tubers remained in the field for two weeks to mature before mechanical harvest using a Braco® single-row bagger unit harvester. A mechanical sorter was used to wash, count and weigh each tuber. U.S. No. 1 yield (> 113-g tubers), U.S. No. 2 yield (> 113-g tubers), total marketable yield (U.S. No. 1 + No. 2 + < 113-g tubers), and tuber numbers were compiled for each plot. Treatment (cultivar and spacing) effects on tuber size distributions were assessed by comparing the yields of < 113 g, 113–170 g, 170–284 g, 284–340 g, 340–397 g, and > 397 g tubers on both an absolute (MT ha^{-1}) and relative (percentage of marketable yield) basis.

Bruise Evaluations

Ten tubers of each of three size classes (198–283 g, 284–397 g, and > 397 g) from each plot ($n = 30$ tubers plot^{-1}) were collected at harvest, peeled, and evaluated for the presence of blackspot and shatter bruise. Percent bruise was calculated based on visual observations for the presence or absence of blackspot bruise (≥ 5 mm diameter) and shatter bruise (≥ 3 mm long fissures).

Financial Evaluation

Crop values were quantified as described by Pavek et al. (2018) with a bruise-free incentive added to the contract. In short, the mock frozen-processing contract for long season russeted potatoes in the Columbia Basin (WA) used total yield, marketable yield, and tuber size distribution for estimating percent returns. Specific gravity was not included in the economic analyses. Individual tuber weight data were used to calculate yields of the various tuber size classes, including undersize (< 113 g) and as a percentage of U.S. No. 1 and U.S. No. 2 yields, to determine the premiums and penalties for each in-row spacing. This data was then combined to determine overall crop value at each spacing after subtracting seed cost (see below) and the appropriate premium or penalty for blackspot bruise. Shatter bruise was not considered in the frozen-processing contract as per industry practice (personal communication). The contract stipulations were as follows for the yield and size distribution values: base price was U.S. $146.61 MT^{-1} with a less than 113-g tuber value of U.S. $66.14 MT^{-1}. The premium for greater than 170-g tubers was a maximum of U.S. $13.23 MT^{-1} with an additional incentive maximum of U.S. $11.02 MT^{-1} for U.S. No. 1 tubers greater than 170 g. For Ranger Russet, tuber blackspot bruise penalty or premium ranged from a low of U.S. -$11.02 MT^{-1} for 28% bruise free and increased by U.S. $0.55 for every 1% increase in bruise free until 48% after which, the incentive increased U.S. $0.88 for every 1% increase in bruise free to a maximum of U.S. $32.19 MT^{-1} at ≥ 88% bruise free. For Alturas and Clearwater Russet, the blackspot bruise penalty or premium ranged from U.S. -$11.02 for 35% bruise free and increased by U.S. $0.55 for every 1% increase in bruise free until 55% after which, the incentive increased U.S. $0.80 for every 1% increase in bruise free to a maximum of U.S. $17.70 MT^{-1} for ≥ 77% bruise free. The reject levels were < 28% bruise free for Ranger and < 35% bruise free for Alturas and Clearwater Russet. Seed was valued at U.S. $440.92 MT^{-1} and the seed cost associated with each spacing treatment was subtracted to derive final crop values. The effects of cultivar and spacing on frozen process values are reported relative to Ranger Russet (= 100%) planted at 28-cm in-row spacing (industry standard).

Estimations of the effects of in-row spacing on value as seed potatoes was based on a mock contract for seed that stipulated U.S. $396.83 MT^{-1} for tubers < 113 g, U.S. $330.69 MT^{-1} for 113–340-g tubers, and U.S. $165.35 MT^{-1} for tubers greater than 340 g. Bruise was not considered in the seed contract. Treatment effects on seed crop values are reported relative to Ranger Russet (= 100%) planted at 20-cm in-row spacing.

Data Analysis

Data were subjected to two-way factorial analyses of variance (ANOVA using JMP 15.2) with single degree-of-freedom contrasts to characterize the effects of cultivar (planned comparisons), spacing (including polynomial trends), and their interaction. Fisher's LSD values ($P < 0.05$) are included to separate overall treatment means (cultivar x spacing) and means representing the main effects of cultivar, where appropriate. Since cultivar and spacing effects were similar in 2021 and 2022, the year-to-year variation was removed by blocking in ANOVA and the data are averaged across years. Regression analysis with coefficients of determination (R^2) and *P*-values for correlation coefficients are reported for the effects of spacing on tuber number per plant, total yield, bruise, and crop values averaged across cultivars.

Results

Stem Numbers Per Plant

While significant, the effects of cultivar and in-row spacing on the number of stems plant^{-1} were small. Clearwater Russet at 20 cm spacing produced the most stems per plant (3.0) and Ranger Russet at 43 cm produced the fewest stems per plant (2.3) (Table 1). Clearwater Russet averaged 2.8 stems per plant across the in-row spacings while Ranger Russet and Alturas averaged 2.4 and 2.5 stems per plant, respectively ($LSD_{0.05} = 0.1$, Table 1). When averaged across cultivar, stem numbers decreased linearly from 2.7 to 2.4 as in-row spacing increased from 20 to 43 cm (Table 1; $P < 0.001$).

Tuber Number and Weight

Cultivar and in-row spacing significantly affected average tuber weight, tuber number per plant, and tuber number per hectare (Table 1). Averaged over cultivar, the number of tubers per plant increased from 10.6 to 14.8 (39.6%) as in-row spacing increased from 20 to 43 cm. Conversely, the number of tubers per hectare fell by 32% as spacing increased due to the associated reduction in plant population density. An in-row spacing of 20 cm resulted in an average of 601,819 tubers ha^{-1} compared with 407,056 tubers ha^{-1} for the 43 cm in-row spacing, a difference of 194,762 tubers. Average tuber weight (g tuber^{-1}) increased from 178 to 204 g (14.3%) as spacing increased from 20 to 43 cm, which contributed to a shift in tuber size distribution profiles toward the larger tuber size classes as a percentage of total yield (see below, Fig. 1).

Clearwater Russet produced the smallest potatoes (169.2 g tuber^{-1}) and Ranger Russet the largest potatoes (216.6 g tuber^{-1}) when averaged across spacing treatments (Table 1). On average, Alturas produced the most tubers per plant (16.2) and per hectare (613,770), while Ranger Russet produced the fewest tubers per plant and per hectare (10.1 and 385,761, respectively) across spacings. Importantly, the increases in tuber number per plant with increasing plant spacing depended on cultivar (Alt/RRCW*S_{LT}, $P < 0.001$, Table 1). Alturas increased tuber set the most, adding 2.2 tubers plant^{-1} for every 8 cm increase in seed spacing (Alt tubers plant^{-1} = 7.407 + 0.2785(cm), $R^2 = 0.98$, $P < 0.01$) compared with a combined average of 1.2 tubers plant^{-1} (RR*CW tubers plant^{-1} = 6.596 + 0.1469(cm), $R^2 = 0.97$, $P < 0.01$) for Ranger and Clearwater Russet.

Yields and Tuber Size Distributions

Total marketable yields (U.S. No. 1 and 2, plus < 113 g) were significantly affected by cultivar and spacing treatments (Table 1). Alturas produced the highest marketable yield of 125.5 MT ha^{-1}, while yields from Ranger and Clearwater averaged 91.0 and 87.7 MT ha^{-1}, respectively, over the spacing treatments (Alt/RR*CW, $P < 0.001$). Similarly, the average U.S. No. 1 yield of Alturas (85.4 MT ha^{-1}) was higher than either Ranger (73.0 MT ha^{-1}) or Clearwater Russet (71.3 MT ha^{-1}) whose yields were equivalent. Alturas, however, averaged 23.7 MT ha^{-1} of U.S. No. 2 tubers (= 18.9% of marketable yield), which was substantially higher than the 8.8 MT ha^{-1} (9.7% of marketable) produced by Ranger and 2.4 MT ha^{-1} (2.7% of marketable) from Clearwater Russet.

Tuber size distributions changed with in-row spacing treatments. As in-row spacing increased, the yields of < 113 g, 113–170 g, and 170–284 g tubers declined linearly ($P < 0.001$) for all cultivars with little to no effect on the yields of 284–340 g, 340–397 g, and > 397 g tubers (Table 1, Fig. 1). Collectively, these effects accounted for the linear declines in overall marketable yields with increased spacing (Table 1; MT ha^{-1} = 134.7 – 1.0494(cm), $R^2 = 0.85$, $Spacing_{LT}$ $P < 0.001$). The reductions in marketable yields are clearly represented in Fig. 1 by the reduction in areas of the tuber size distribution polygons (MT ha^{-1}) with wider spacing for each cultivar. Increasing the plant spacing from 20 to 43 cm resulted in a 30.3% decrease in total marketable yield across all cultivars, with Ranger and Clearwater Russet averaging 24.2% reduction, versus a 21.8% reduction in the total yield of Alturas (Table 1, Fig. 1).

When normalized to total marketable yield (i.e. % yield), the tuber size distribution profiles for Ranger Russet were characterized by higher percentages of oversize (> 397 g) and 170–284 g tubers (Fig. 1) relative to the other tuber size classes. In contrast, the size distribution profiles of Clearwater Russet were skewed toward higher percentages of 170–284 g, 113–170 g, and < 113 g tubers, while those of Alturas favored the > 397 g, 170–284 g, 113–170 g, and < 113 g tuber size classes. As in-row spacing increased from 20 to 43 cm, the percent yields of < 113 g, 113–170 g, and 170–284 g Ranger Russet tubers decreased with a concomitant increase in the percentage of oversize (> 397 g) tubers (Fig. 1). Similarly, shifts in the tuber size distribution of Clearwater Russet with increasing spacing were characterized by a decrease in the percentages of < 113 g and 113–170 g tubers in favor of higher percentages of > 170 g tubers. For Alturas, increases in in-row spacing decreased the percentage of < 113 g and 113–170 g tubers and

Table 1 Effects of in-row seed spacing (S) and cultivar (CV) on stem and tuber numbers, tuber weight, and yields for cvs. Ranger Russet (RR), Clearwater Russet (CW), and Alturas (Alt). Seed was planted April 19, 2021, and April 20, 2022. Vines were mowed 147 days after planting and tubers were harvested 2 weeks later. ANOVA results are summarized beneath the table

			Tuber Yields (MT ha^{-1}) (2021 and 2022 seasons)									Marketable tubers[a]		
Cultivar (CV)	Spacing (cm)	Stems plant^{-1}	Mkt[a]	U.S. #1[b]	U.S. #2[b]	< 113 g	113–170 g	170–284 g	284–340 g	340–397 g	> 397 g	g tuber^{-1}	plant^{-1}	1000's ha^{-1}
Ranger	20	2.5	107.4	84.4	11.3	11.7	14.9	32.7	13.1	10.1	25.1	203	8.5	481.0
	28	2.4	87.9	69.8	8.4	9.8	11.1	24.0	11.7	8.4	23.0	206	9.6	386.7
	36	2.4	88.5	73.0	7.0	8.5	10.4	24.4	11.2	9.2	24.7	219	11.2	368.6
	43	2.3	80.1	64.8	8.6	6.6	8.7	18.6	9.5	8.1	28.5	238	11.2	306.8
Clearwater	20	3.0	100.7	75.9	5.5	19.3	22.6	35.2	8.8	5.5	9.3	157	10.2	580.4
	28	2.8	86.4	70.2	0.8	15.4	19.2	30.7	8.7	5.6	6.8	160	12.1	489.0
	36	2.7	86.0	72.3	1.9	11.8	15.4	31.8	11.3	6.0	10.0	178	13.2	434.5
	43	2.7	77.6	66.9	1.4	9.3	15.0	29.4	8.2	5.8	9.5	182	14.1	386.0
Alturas	20	2.5	142.2	93.3	27.0	21.9	27.5	46.2	14.4	9.5	22.8	175	13.1	744.1
	28	2.5	123.2	83.6	23.4	16.2	22.3	37.0	13.5	8.2	25.9	190	14.8	594.9
	36	2.4	125.5	86.9	24.1	14.5	21.3	41.9	12.7	9.2	26.0	197	17.9	587.7
	43	2.4	111.1	77.9	20.1	13.0	19.5	35.7	12.0	9.8	21.1	192	19.2	528.4
$LSD_{0.05}$[c]		0.2	13.7	14.4	8.4	3.4	4.0	7.0	3.5	3.2	9.7	22	1.4	49.0
CV $LSD_{0.05}$		0.1	6.8	7.2	4.2	1.7	2.0	3.5	1.7	1.6	4.8	11	0.7	24.5
Alt/RR*CW[d]		0.05[e]	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.05	0.01	ns	0.001	0.001
RR/CW		0.001	ns	ns	0.01	0.001	0.001	0.001	0.05	0.001	0.001	0.001	0.001	0.001
Spacing LT		0.001	0.001	0.01	0.1	0.001	0.001	0.001	0.1	ns	ns	0.001	0.001	0.001
Spacing QT		ns	ns	ns	ns	ns	0.1	ns	ns	ns	ns	ns	ns	0.01
Spacing Dev		ns	0.05	0.1	ns	ns	ns	0.05	ns	ns	ns	ns	ns	0.05
Alt/RRCW*S_{LT}		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.001	ns
RR/CW*S_{LT}		ns	ns	ns	ns	0.05	ns	ns	ns	ns	ns	ns	ns	ns

[a] Total marketable yield (Mkt) = U.S. No.1 + U.S. No. 2 + undersize (< 113 g) tubers. Cull tubers are not included. [b] U.S. No. 1 or 2 yield larger than 113 g. [c] $LSD_{0.05}$, Least Significant Difference at $P < 0.05$. The overall LSD and the LSD for the main effect of cultivar are given. [d] Sources of variation for single degree-of-freedom (df) planned comparisons (LT, linear trend; QT, quadratic trend; Dev, deviations). Only those contrasts that significantly affected one or more of the agronomic variables are shown. [e] *P*-values for the single df contrasts (ns, not significant)

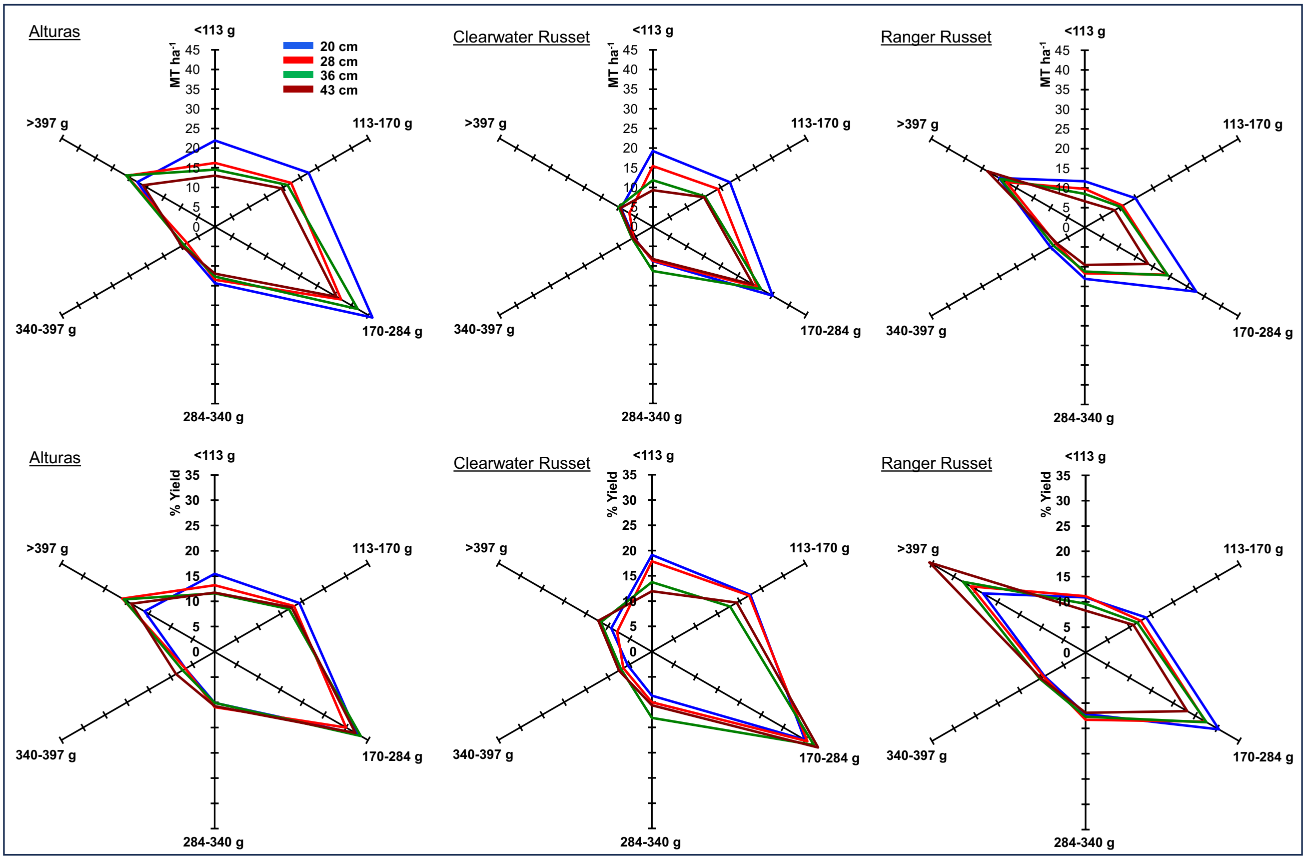

Fig. 1 Radar graphs that portray the effects of four in-row seed spacings on the yields and tuber size distribution profiles of *cvs* Alturas, Clearwater Russet, and Ranger Russet. The marketable yields of < 113 g, 113–170 g, 170–284 g, 284–340 g, 340–397 g, and > 397 g tubers are plotted as MT ha^{-1} (top row) and as a percentage of total marketable yield (bottom row). See Table 1 for yields and ANOVA results

increased the percentage yields of 340–397 g and > 397 g tubers.

Tuber Bruise

The average total yield of bruised tubers (blackspot + shatter) was higher ($P < 0.05$) for Alturas (61.5 MT ha^{-1}) than for Ranger (52.3 MT ha^{-1}) and Clearwater Russet (51.8 MT ha^{-1}) (Table 2). Moreover, shatter bruise was much more extensive than blackspot bruise for all cultivars. Alturas averaged 58.5 MT ha^{-1} shatter bruise versus 49.9 and 37.3 MT ha^{-1} for Clearwater and Ranger Russet, respectively ($LSD_{0.05} = 7.5$ MT ha^{-1}). By comparison, the average yield of blackspot-bruised tubers of Alturas was only 3.0 MT ha^{-1}, which was comparable to Clearwater (1.9 MT ha^{-1}) but significantly lower than Ranger (14.0 MT ha^{-1}). Alturas, however, produced the lowest total bruise (49.1%) when normalized as a percentage of marketable yield and compared to Clearwater (59.2%) and Ranger (57.4%) (Table 2, $LSD_{0.05} = 6.7\%$).

Despite the increase in average tuber weight (Table 1) and associated shifts in yield profiles toward larger size tubers (Fig. 1) with wider in-row spacings, total bruise fell by an average of 4.4 MT ha^{-1} for every 8-cm increase in in-row spacing from 20–43 cm (Table 2) (Bruise MT $ha^{-1} = 72.6 - 0.5468(\text{cm})$, $R^2 = 0.85$, Spacing_{LT} $P < 0.05$). This decline in bruise yield was mainly attributable to the reduction in total marketable yields with wider spacings (Table 1) and the two were highly correlated (Bruise MT $ha^{-1} = 2.21 + 0.5228$(Mkt Yld MT ha^{-1}), $R^2 = 0.99$, $P < 0.01$). Therefore, total bruise as a percentage of marketable tuber yield remained relatively constant (at ca. 55%) across in-row spacing (Table 2).

Detailed evaluations of the extent of blackspot versus shatter bruise across three tuber size classes revealed the highest average total yield of tubers with blackspot bruise at 20 cm in-row spacing, with only the 284–397 g tubers of Ranger Russet significantly affected by spacing treatments ($P < 0.01$; Table 2). However, in-row spacing had no effect on the total yields of blackspot-bruised tubers. In contrast, the total yield of tubers with shatter bruise fell linearly by 3.5 MT ha^{-1} for every 8-cm increase in in-row spacing

Table 2 Effects of in-row seed spacing (S) and cultivar (CV) on yields of tubers with blackspot, shatter, and total bruise for tubers ≥ 198 g. ANOVA results are summarized beneath the table

Cultivar (CV)	Spacing (cm)	Total Bruise (MT ha^{-1})	Total Bruise (%)	Blackspot Bruise Yield (MT ha^{-1})[a]					Shatter Bruise Yield (MT ha^{-1})[a]				
				198-284 g	284-397 g	> 397 g	Total[b]	%	198-284 g	284-397 g	> 397 g	Total[b]	%
Ranger	20	64.1	59.6	3.7	3.7	6.0	19.2	17.8	8.7	9.1	12.9	44.9	41.8
	28	48.6	55.3	4.7	1.9	3.8	13.6	15.5	4.3	8.6	12.7	35.0	39.8
	36	49.4	55.9	3.0	4.7	4.7	17.6	19.9	6.3	6.7	9.8	31.8	36.0
	43	47.1	58.8	1.5	2.3	3.7	9.6	12.0	6.4	8.6	14.2	37.5	46.9
Clearwater	20	56.7	56.3	0.5	0.2	0.9	2.4	2.4	12.1	7.9	4.8	54.3	54.0
	28	50.9	59.0	0.6	0.3	0.2	1.6	1.9	12.1	7.5	4.4	49.3	57.1
	36	57.1	66.4	1.2	0.4	0.3	2.6	3.0	12.6	10.8	7.5	54.5	63.4
	43	42.7	55.0	0.2	0.2	0.2	1.0	1.4	9.8	6.6	7.0	41.6	53.6
Alturas	20	69.0	48.6	0	1.5	0.7	3.6	2.5	13.8	11.6	12.5	65.5	46.0
	28	62.5	50.8	0	0	2.1	1.7	1.4	14.4	8.5	12.8	60.8	49.3
	36	57.0	45.4	0	0.9	0.7	2.9	2.3	11.4	9.9	12.6	54.1	43.1
	43	57.4	51.6	0	0.5	2.2	3.6	3.3	13.7	10.3	11.3	53.7	48.4
$LSD_{0.05}$[c]		17.5	13.4	2.1	2.1	3.6	7.2	6.0	5.1	4.8	6.9	15.0	11.0
CV $LSD_{0.05}$		8.7	6.7	1.0	1.0	1.8	3.6	3.6	2.6	2.4	3.5	7.5	5.8
Alt/RR*CW[d]		0.05[e]	0.001	0.001	0.05	ns	0.001	0.001	0.001	0.1	0.05	0.001	ns
RR/CW		ns	ns	0.001	0.001	0.001	0.001	0.001	0.001	ns	0.001	0.01	0.001
Spacing LT		0.05	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.05	ns
Spacing QT		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Spacing Dev		ns	ns	ns	0.01	ns	ns	0.1	ns	ns	ns	ns	ns
RR/CW*S_{LT}		ns	ns	0.1	ns	ns	ns	ns	ns	ns	ns	ns	ns
RR/CW*S_{Dev}		ns	ns	ns	0.05	ns	ns	ns	ns	ns	ns	ns	0.1

[a] Blackspot and shatter bruise were evaluated on five replications of ten randomly selected tubers from each size category ($n = 50$ tubers). [b] Total blackspot and shatter bruise yields were calculated from the bruise percentages. [c] $LSD_{0.05}$, Least Significant Difference at $P < 0.05$. The overall LSD and the LSD for the main effect of cultivar are given. [d] Sources of variation for single degree-of-freedom (df) planned comparisons (LT, linear trend; QT, quadratic trend; Dev, deviations). Only those contrasts that significantly affected one or more of the agronomic variables are shown. [e] *P*-values for the single df contrasts (ns, not significant)

(Shatter MT ha^{-1} = 62.4 – 0.4357(cm), $R^2 = 0.92$, Spacing$_{LT}$ $P < 0.05$) but spacing had no effect on shatter within each of the three size classes (Table 2). Like total bruise percentage (see above), the percentages of shatter and blackspot were not affected by in-row spacing.

Since spacing had little to no effect on the extent of blackspot and shatter bruising within the 198–284 g, 284–397 g, and > 397 g tuber size classes (Table 2), bruised tuber yields (MT ha^{-1}) were summed across spacings and expressed as percentages of the total marketable yields of each size class to reveal the effects of tuber size on bruising for each cultivar (Fig. 2). The overall effect of tuber size class on percent total bruise (Fig. 2a) was highly significant ($P < 0.001$). On average, tubers > 397 g had the highest percent bruise damage (63%) followed by the 284–397 g and 198–284 g tubers (52% and 50%, respectively). However, the extent to which the percentages of bruised tubers increased with tuber size depended on cultivar and bruise type. Clearwater Russet and Ranger Russet tubers > 397 g had the greatest total bruise (69% and 66%, respectively) followed by Alturas (54%; Fig. 2a). Moreover, the percentages of total and shatter bruise in Ranger increased linearly ($P < 0.01$) as tuber size increased from 198–284 g to > 398-g tubers (Fig. 2ab). Blackspot bruise also increased linearly with increasing tuber size class in Alturas ($P < 0.05$); however, the percentage of shatter bruise remained relatively constant at ca. 46% across the tuber size classes for this cultivar (Fig. 2b). Interestingly, in-row spacing had no effect on the percent total bruise by tuber size class (data not shown). On average, Ranger had the highest blackspot bruise (16%; $P < 0.001$) followed by Alturas (3%) and Clearwater Russet (2%; Fig. 2c). Clearwater had the most shatter bruise (58%; $P < 0.001$) compared to Ranger Russet and Alturas, which averaged 46% and 41%, respectively. Across cultivars, tubers > 397 g averaged 54% shatter bruise, which was significantly ($P < 0.001$) higher than the 46% for 284–397 g and 44% for 198–284 g tubers (Fig. 2b).

Estimation of Financial Values

Estimates of the effects of cultivar and in-row spacing on financial returns (U.S.$ ha^{-1}) were based on mock contracts for seed and frozen-processing potatoes. Total marketable yield, percentage yield of U.S. No. 1 tubers, premiums or penalties for tuber size distribution and blackspot bruise (not shatter), and seed costs were factored into the contracts where appropriate. The crop values are shown normalized to Ranger Russet (= 100) planted at 28 cm for frozen process (Fig. 3a) and 20 cm for seed (Fig. 3b). After subtracting seed costs, the relatively low percentages of blackspot bruise (Table 2, Fig. 2) triggered bruise-free incentives (no penalties) in the mock contract, which increased crop values by an average of 15% across cultivars and in-row spacings.

For French fry processing, Alturas had the greatest return averaged over in-row spacing treatments (cultivar $P < 0.001$), though specific gravity, postharvest quality, and input-use efficiency (e.g. nitrogen) were not included in the financial analyses. On average, the return for Alturas was 24% higher than Ranger, and 47% higher than Clearwater Russet with blackspot bruise incentives and seed costs included in the contracts (Fig. 3a). The effect of cultivar remained significant ($P < 0.001$) even before adjusting for seed costs and blackspot bruise, with Alturas producing 27% higher return than Ranger ($P < 0.01$) and Ranger producing 13% higher return than Clearwater Russet ($P < 0.05$).

When averaged across cultivars, frozen processing returns decreased with increasing in-row spacing ($P < 0.05$ Spacing$_{LT}$) and no cultivar x spacing interactions were significant (Fig. 3a). The frozen processing returns were most influenced by and thus correlated with

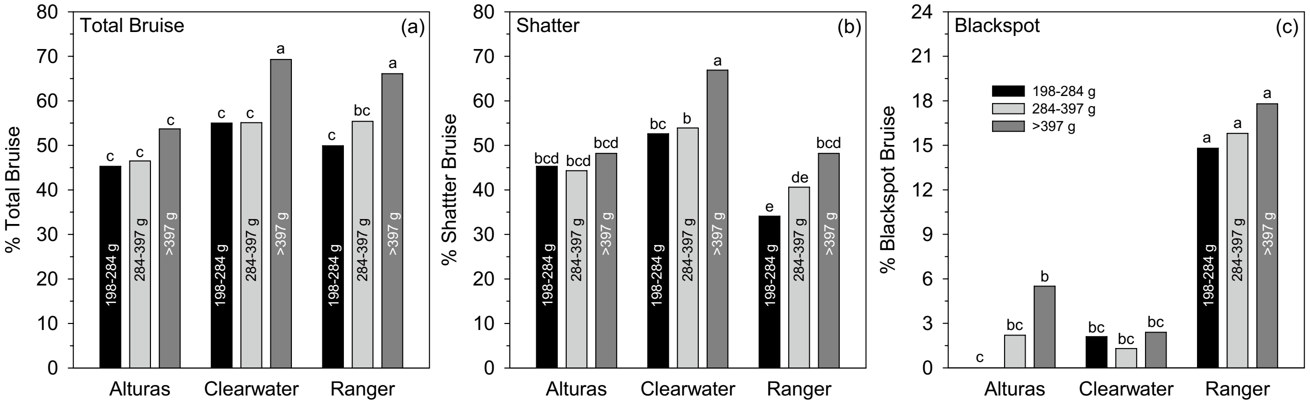

Fig. 2 Effects of cultivar and tuber size class on total bruise (**a**), shatter bruise (**b**), and blackspot bruise (**c**) expressed as a percentage of the yield of each size class. ANOVA results for total, shatter, and blackspot bruise: cultivar, $P < 0.01$; tuber size class, $P < 0.05$; cultivar x size class (linear), $P < 0.01$. Letters indicate LSD, $P < 0.05$ across cultivars and size classes within a bruise type. Note that the Y-axis range for blackspot bruise (c) differs from that for total (a) and shatter bruise (b)

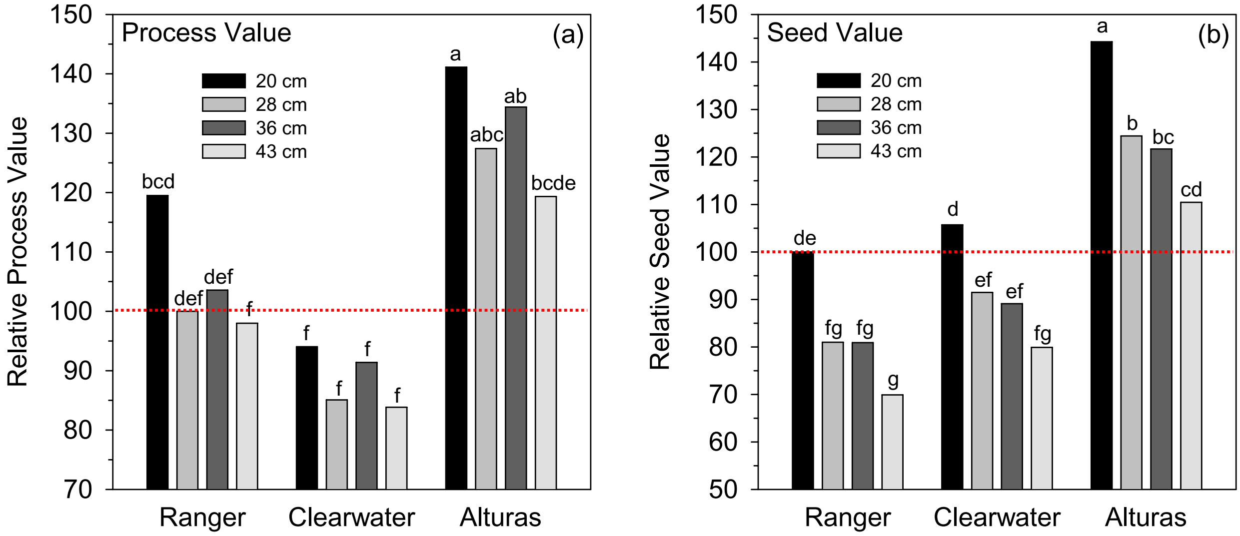

Fig. 3 Effects of cultivar and in-row spacing on economic returns (U.S.$ ha^{-1}) based on mock contracts for frozen-processing (**a**) and seed potatoes (**b**). The relative values have been normalized to Ranger Russet (=100%) planted at 28 and 20 cm for the frozen process and seed crops, respectively (red dotted lines for clarity). Seed costs associated with the different in-row spacings were subtracted to derive the net values shown. Blackspot bruise-free incentives/penalties were included in the frozen processing contract. Letters indicate LSD, $P<0.05$ across cultivars and size classes within a bruise type

($R^2=0.88$, $P<0.01$) changes in total marketable yields as affected by in-row spacing (Table 1, Fig. 1) across cultivars. Moreover, the \$ ha^{-1} return for every MT ha^{-1} increase in yields of Ranger Russet and Alturas were 78% higher on average than that for Clearwater Russet, which likely reflects the more favorable size distribution profiles (Fig. 1) of the former two cultivars for frozen processing.

In contrast to the frozen-processing contract, bruise clauses were not included in estimating the effects of cultivar and in-row spacing on crop value as seed potatoes. Therefore, cultivar and in-row spacing affected seed values primarily by modifying total marketable yields, tuber size distributions (esp. the relative yields of < 113, 113–340, and > 397-g tubers), and seed costs. Like frozen-processing returns, changes in seed values (Fig. 3b) were proportional to the relative yields of individual size classes (< 113 g and 113 to 340 g) and the total marketable yields as affected by treatments. The only variation from this trend were tubers > 340 g where both Ranger Russet and Alturas produced equivalent seed crop values in oversized seed, though greater than Clearwater Russet ($P<0.001$), and in-row spacing had no significant effect on the oversized seed values. Consistent with its higher marketable yield, Alturas produced the highest valuation on a seed contract, followed by Clearwater and Ranger ($P<0.01$). For all cultivars, seed values were highest at 20-cm spacing and declined linearly as spacing increased to 43 cm (Fig. 3b, Spacing_{LT} $P<0.001$).

Discussion & Conclusions

This study was conducted to characterize and compare how in-row spacing affects yield, tuber size distribution, bruise damage, and financial returns for three processing cultivars of commercial importance in the Columbia Basin of Washington. While these cultivars can vary for process timing at the factory (e.g. field direct for Ranger Russet vs storage of Alturas and Clearwater), treatment effects on bruise and economic returns were assessed only once (at harvest) for all three cultivars.

As expected, the effects of spacing on total marketable yield, percent bruise (blackspot and shatter), and relative financial returns were cultivar dependent. Clearwater Russet had the lowest processing value, the highest percentage of shatter bruise, and produced the smallest tubers (both on average and for percent undersize (< 113 g)). Ranger Russet had the lowest seed value and the highest percentage of blackspot bruise. Interestingly, while the percent total bruise (blackspot + shatter) was the same for Clearwater and Ranger Russet, shatter accounted for a higher percentage of the total bruise in Clearwater, and this had no effect on its process value since shatter bruise was not a component of the bruise incentive in the contract. Alturas produced the highest process and seed values due primarily to its higher marketable yield than the other cultivars. Shatter and blackspot bruise averaged 46.7 and 2.7%, respectively, in Alturas.

Consistent with previous work (Knowles and Knowles 2016; Love and Thompson-Johns 1999), wider in-row spacing increased the number of tubers per plant, reduced the number of tubers per hectare, and increased the average tuber weight for all cultivars. The reduction in tuber number per plant with closer in-row spacing may be a response to increased competition for agronomic resources (e.g. water and nutrients) at the higher planting density, while wider spacing allowed more space for tuber bulking and thus reduced plant-to-plant competition. The mechanism by which potato plants modulate tuber set in response to changes in plant density is unknown; however, the ability to control this response has tremendous implications for precision management of tuber size and thus warrants further investigation.

The increase in bruise yield (MT ha^{-1}) with closer spacing was primarily due to shatter bruise, which accounted for 64 to 97% of total bruise depending on cultivar and in-row spacing. The yields of blackspot bruised tubers were largely unaffected by spacing and despite the cultivar differences (Ranger was highest), blackspot remained well below the levels (53 to 72% bruise) at which financial penalties (i.e. negative \$ MT^{-1}) would be applied in the frozen processing contract. In fact, the low levels of blackspot (range = 1.4 to 19.9%) triggered bruise-free incentives (not penalties) in the contracts, which enhanced the frozen-processing values by an average of 18.7% for Ranger versus 14.0 and 13.5% for Clearwater and Alturas, respectively. This result is somewhat counterintuitive given that Ranger had significantly higher blackspot bruise than the other cultivars (Table 2). However, the dollar incentive stipulations for a given percentage of bruise-free were substantially higher in the contract for Ranger versus Clearwater and Alturas (see Materials and Methods). For example, 85% bruise free (15% blackspot) on the Ranger contract boosted the overall crop value by \$29.77 MT^{-1} versus only \$17.70 MT^{-1} for Alturas and Clearwater. The levels of blackspot in Alturas (2.4%) and Clearwater (2.2%) were sufficiently low to trigger the maximum incentive of \$17.70 MT^{-1} for both cultivars. However, Ranger averaged 16.3% bruise (83.7% bruise free) over the in-row spacings (Table 2), which added \$28.97 MT^{-1} incentive to the contract, but this incentive was still \$3.22 lower than the maximum possible incentive of \$32.19 MT^{-1} for ≥ 88% bruise-free. Therefore, the relative process value of Ranger (Fig. 3) could have been significantly higher by reducing the percentage of blackspot bruise. Furthermore, had shatter bruise and blackspot bruise both been considered as ‘bruise’ in the financial model, then significant penalties would have been triggered in this study.

Past research has demonstrated that drop distance, chain speed, and tuber size are factors which can greatly influence bruise damage (Thornton 1996; Hendricks et al 2022), especially in tubers larger than 340 g (Baritelle and Hyde 1999). In this study, the incidence of bruise was greatest in the larger tuber size classes, though not high enough to invoke negative financial penalties. Nevertheless, it is important to acknowledge the potential negative downstream effects of increased bruise on crop value (frozen processing) and seed (performance issues) for stored potatoes. Spacing affected tuber size distributions and bruise incidence was higher in the larger tuber size classes. Therefore, in-row spacing decisions, and for that matter any production factors or management practices (e.g. seed physiological age, plant growth regulator treatments, etc.) that affect tuber size distributions will likely also affect bruise levels (blackspot and shatter) going into storage, which in turn affects losses due to shrink (Brooke 1996), pressure bruise (Thornton and Bohl 1998), and disease (e.g. fusarium, soft rot, etc.) (Corsini 1996; Nolte 1996). In the case of seed potatoes, the loss of productive potential attributed to bruise damage in the seed crop has been estimated as high as 21% (Nolte 1996; Halderson 1996). While larger potato tubers are generally more susceptible to bruising due to greater impact forces and potential for mechanical damage, knowledge of expected tuber size distribution profiles, careful handling, and optimized harvesting practices can mitigate these risks. Future studies should focus on the full financial impact of bruise, including special consideration for shatter bruise as it relates to storage losses with pathogen infection, shrink, and attenuation in seed productivity.

Commercially, growers are routinely advised to keep equipment belts full of potato tubers to limit damage (blackspot and shatter bruise; Thornton and Bohl 1998). The observations from this study are interesting because increased total marketable yield (due to tighter in-row spacing) likely increased tuber loading on harvest equipment but the impact on the percent total damage was constant regardless of crop load on the harvester. One possible explanation could be the role of individual drop points contributing to the damage, which was not investigated here. Past work (Halderson 1996) suggests that impact velocity has a greater effect on damage than tuber size, with high velocity impacts causing shatter bruise and low velocity impacts causing blackspot bruising. Other factors may include plant fertility, inadequate skin set, use of padding at transition points, and maintaining tuber core temperatures at 7.2–18.3 °C (Dean 1996; Thornton and Bohl 1998). With these considerations in mind, especially fertility, results from this study and others contrast with the results from Bolding (2017) and Hatch (2017) for Clearwater Russet. Both Bolding and Hatch factored in the cost of nitrogen management with plant spacing and observed that higher planting densities required additional fertility inputs, which ultimately affected crop value. These studies, however, did not consider bruise damage in the economic evaluations. Ideally, to maximize returns in the various end-use markets, cultivar-specific in-row spacing recommendations should balance the full array of input costs associated with producing a target tuber size profile and minimum bruise before being adopted.

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Declarations

Conflict of interest The authors declare no conflict of interest.

Disclaimers Data is the result of original research conducted by the authors and there are no known conflicts of interest related to this work nor its publication.

References

Baley, N., V. Sathuvalli, B.A. Charlton, C.C. Shock, S. Yilma, R. Qin, E. Feibert, M.I. Vales, R.G. Novy, J.L. Whitworth, C. Brown, D.A. Navarre, J.C. Stark, M.J. Pavek, N.R. Knowles, L.O. Knowles, J.M. Blauer, T.L. Brandt, Y. Wang, M. Thornton, R.R. Spear, and N. Olsen. 2023. Echo Russet: A russet potato variety with a high yield of marketable tubers, high processing quality, an few tuber defects. *American Journal of Potato Research* 100: 15–26. https://doi.org/10.1007/s12230-022-09891-2.

Baritelle, A.L., and G.M. Hyde. 1999. Effect of tuber size on failure properties of potato tissue. *American Society of Agricultural Engineers* 42 (1): 159–161.

Blauer, J.M., V. Sathuvalli, B.A. Charlton, S. Yilma, C.C. Shock, N. Baley, R. Qin, E. Feibert, R.G. Novy, J.L. Whitworth, M.J. Pavek, N.R. Knowles, L.O. Knowles, N. Fuller, J.C. Stark, R.R. Spear, M. Thornton, N. Olsen, S. Jayanty, D.A. Navarre, M.J. Feldman, and I. Vales. 2024. Rainier Russet: A dual use russet potato with long tuber dormancy, excellent process quality, and high early harvest packaging efficiency. *American Journal of Potato Research* 101: 17–33. https://doi.org/10.1007/s12230-023-09935-1.

Bohl, W.H., J.C. Stark, and C.S. McIntosh. 2011. Potato seed piece size, spacing, and seeding rate effects on yield, quality, and economic return. *American Journal of Potato Research* 88: 470–478. https://doi.org/10.1007/s12230-011-9213-4.

Bolding, K.R. 2017. Chapter 3: In-row spacing and nitrogen recommendations for Clearwater Russet when grown in the Columbia Basin. Master of Science Thesis. Fine-tuning the cultural management of Russet Burbank and Clearwater Russet potatoes by investigating in-row spacing, seed-type, and/or nitrogen rate. Washington State University. pgs 43–68. https://rex.libraries.wsu.edu/esploro/outputs/graduate/Fine-tuning-the-cultural-management-of-russet/99900525283101842#file-0.

Brooke, R.C. 1996. *Bruising leaves mark on potato industry*. Potato Bruising. How and why emphasizing black spot bruise. The National Potato Anti-Bruise Committee: The Potato Association of America. Editor Dr. Roger C. Brook. Running Water Publishing, Haslett, Michigan. ISBN 0-9650498-0-9. pgs 3-7.

Corsini, D. 1996. *The response of potato cultivars to bruising*. Potato Bruising. How and why emphasizing black spot bruise. The National Potato Anti-Bruise Committee: The Potato Association of America. Editor Dr. Roger C. Brook. Running Water Publishing, Haslett, Michigan. ISBN 0-9650498-0-9. pgs 39-44.

Dean, B. 1996. *The chemical nature of black spot bruising*. Potato Bruising. How and why emphasizing black spot bruise. The National Potato Anti-Bruise Committee: The Potato Association of America. Editor Dr. Roger C. Brook. Running Water Publishing, Haslett, Michigan. ISBN 0-9650498-0-9. pgs 29-38.

Ellis, G.D., L.O. Knowles, and N.R. Knowles. 2020. Developmental and postharvest physiological phenotypes of engineered potatoes (*Solanum tuberosum* L.) grown in the Columbia Basin. *Field Crops Research* 250: 107775. https://doi.org/10.1016/j.fcr.2020.107775.

Franc, G. 1996. *Potato storage and black spot bruising*. Potato Bruising. How and why emphasizing black spot bruise. The National Potato Anti-Bruise Committee: The Potato Association of America. Editor Dr. Roger C. Brook. Running Water Publishing, Haslett, Michigan. ISBN 0-9650498-0-9. pgs 83-89.

Gancarz, M. 2016. Correlation between cell size and blackspot of potato tuber parenchyma tissue after storage. *Postharvest Biology and Technology*. 117: 161–167. https://doi.org/10.1016/j.postharvbio.2016.03.004.

Gonzalez T, F., M.J. Pavek, N.R. Knowles, and Z.J. Holden. 2024. Reduced late-season irrigation improves potato quality, often at the expense of yield and economic return. *American Journal of Potato Research* 101: 202–225. https://doi.org/10.1007/s12230-024-09948-4.

Halderson, J. 1996. *Testing methods for bruise determination.* Potato Bruising. How and why emphasizing black spot bruise. The National Potato Anti-Bruise Committee: The Potato Association of America. Editor Dr. Roger C. Brook. Running Water Publishing, Haslett, Michigan. ISBN 0-9650498-0-9. pgs 91-97.

Hatch, J.L. 2017. Chapter 2: Yield, Quality, and Economics. Master of Science Thesis. Effects of seed piece spacing, nitrogen rate, and nitrogen application timing on Clearwater Russet. Theses and Dissertations Collection, Digital Initiatives, University of Idaho Library. pgs 16–48. https://www.lib.uidaho.edu/digital/etd/items/hatch_idaho_0089n_11242.html.

Hendricks, R.L., N. Olsen, M.K. Thornton, and P. Hatzenbuehler. 2022. Susceptibility of potato cultivars to blackspot and shatter bruise at three impact heights. *American Journal of Potato Research* 99: 358–368. https://doi.org/10.1007/s12230-022-09887-y.

Hyde, G.M., R.W. Bajema, and W. Zhang. 1996. *The physics of potato tuber bruising*. Potato Bruising. How and why emphasizing black spot bruise. The National Potato Anti-Bruise Committee: The Potato Association of America. Editor Dr. Roger C. Brook. Running Water Publishing, Haslett, Michigan. ISBN 0-9650498-0-9. pgs 9-27.

Knowles, N.R., M.J. Pavek, L.O. Knowles, and Z. Holden. 2008. Developmental profiles and postharvest behavior of long-season processing cultivars. *In* Proceedings of the 47th Annual Washington State Potato Conference, Feb. 5–7, Moses Lake, WA, pp. 45–66.

https://www.nwpotatoresearch.com/images/documents/Knowles2008.pdf.

Knowles, N.R., C. Dean, L. Knowles, and M. Pavek. 2019. Optimizing crop development and process quality of Clearwater Russet in the Columbia Basin. *In* Proceedings of the 2019 Washington/Oregon Potato Conference. pp. 36–42. https://www.nwpotatoresearch.com/images/documents/Knowles%20et%20al%202019%20Proceedings.pdf.

Knowles, N.R., and L.O. Knowles. 2016. Optimizing tuber set and size distribution for potato seed (*Solanum tuberosum* L.) expressing varying degrees of apical dominance. *Journal of Plant Growth Regulation* 35: 574–585. https://doi.org/10.1007/s00344-015-9562-1.

Lenfesty, C.M. 1967. *Soil survey: Adams county*. Washington: Conservation Service.

Love, S.L., and A. Thompson-Johns. 1999. Seed piece spacing influences yield, tuber size distribution, stem and tuber density, and net returns of three processing potato cultivars. *HortScience* 34 (4): 629–633.

Nolte, P. 1996. *The effect of bruising on seed potato performance.* Potato Bruising. How and why emphasizing black spot bruise. The National Potato Anti-Bruise Committee: The Potato Association of America. Editor Dr. Roger C. Brook. Running Water Publishing, Haslett, Michigan. ISBN 0-9650498-0-9. pgs 45-49.

Novy, R.G., D.L. Corsini, S.L. Love, J.J. Pavek, A.R. Mosley, S.R. James, D.C. Hane, C.C. Shock, K.A. Rykbost, C.R. Brown, and R.E. Thornton. 2003. Alturas: A multi-purpose, russet potato cultivar with high yield and tuber specific gravity. *The American Journal of Potato Research* 80: 295–301.

Novy, R.G., J.L. Whitworth, J.C. Stark, S.L. Love, D.L. Corsini, J.J. Pavek, M.I. Vales, S.R. James, D.C. Hane, C.C. Shock, B.A. Charlton, C.R. Brown, N.R. Knowles, M.J. Pavek, T.L. Brandt, S. Gupta, and N. Olsen. 2010. Clearwater Russet: A dual-purpose potato cultivar with cold sweetening resistance, high protein content, and low incidence of external defects and sugar ends. *The American Journal of Potato Research* 87: 458–471. https://doi.org/10.1007/s12230-010-9148-1.

Pavek, M.J., and R.E. Thornton. 2006. Agronomic and economic impact of missing and irregularly spaced potato plants. *American Journal of Potato Research* 83: 55–66.

Pavek, J.J., D.L. Corsini, S.L. Love, D.C. Hane, D.G. Holm, W.M. Iritani, S.R. James, M.W. Martin, A.R. Mosley, J.C. Ojala, C.E. Stanger, and R.E. Thornton. 1992. Ranger Russet: A long russet potato variety for processing and fresh market with improved quality, disease resistance, and yield. *The American Journal of Potato Research* 69: 483–488.

Pavek, M.J., S. Shelton, Z.J. Holden, and B.J. Weddell. 2018. Impact of canopy destruction from simulated hail on potato yield and economic return. *American Journal of Potato Research* 95: 33–44. https://doi.org/10.1007/s12230-017-9612-2.

Spear, R.R., R.G. Novy, J.L. Whitworth, J.C. Stark, M.J. Pavek, N.R. Knowles, L.O. Knowles, B.A. Charlton, V. Sathuvalli, S. Yilma, M.K. Thornton, N. Olsen, T.L. Brandt, and Y. Wang. 2021. Galena Russet: A long dormancy, dual purpose potato cultivar exhibiting low asparagine, cold-sweetening resistance, and enhanced protein content. *American Journal of Potato Research* 98: 51–63.

Thornton, M., and W. Bohl. 1998. Preventing potato bruise damage. College of Agriculture, University of Idaho Cooperative Extension System Agricultural Experiment Station. Bulletin 725 (Revised). https://idahopotato.com/uploads/media/intl-best-practices-PreventingPotatoBruiseDamage.pdf.

Thornton, M., Hutchinson P.J.S., and N. Olsen. 2020. Harvest Management. *In*: Stark J, Thornton M, Nolte P (eds) Potato Production Systems. Springer nature Switzerland AG. Ch 16: 499–521. https://doi.org/10.1007/978-3-030-39157-7 ISBN 978-3-030-39156-7.

Thornton, R.M. 1996. *The effect of cultural practices.* Potato Bruising. How and why emphasizing black spot bruise. The National Potato Anti-Bruise Committee: The Potato Association of America. Editor Dr. Roger C. Brook. Running Water Publishing, Haslett, Michigan. ISBN 0-9650498-0-9. pgs 51-70.

United States Department of Agriculture. 2011. United States standards for grades of potatoes. https://www.ams.usda.gov/sites/default/files/media/Potato_Standard%5B1%5D.pdf. Accessed 10 Aug 2024.

USDA-National Agricultural Statistic Service. 2023a. Press Release – 2022 Annual Crop Summary. United States Department of Agriculture. Washington, DC 20250. Northwest Regional Field Office. Olympia, WA 98507. https://www.nass.usda.gov/Statistics_by_State/Washington/Publications/Current_News_Release/2023/CP01.pdf. Accessed 14 June 2023.

USDA-National Agricultural Statistic Service. 2023b. Database - Statistics by Subject - Crops and Plants. Years 2017-2022. National Statistics for Potatoes. https://www.nass.usda.gov/Statistics_by_Subject/result.php?8E2DE647-1408-3767-B50C-B18FB28CA2F5&sector=CROPS&group=VEGETABLES&comm=POTATOES. Accessed 14 June 2023.

Webster, I. 2024. *CPI Inflation Calculator.* Official Data Foundation. https://www.officialdata.org/us/inflation/1996. Accessed 10 June 2024.

Whitworth, J.L., R.G. Novy, J.C. Stark, M.K. Thornton, N.R. Knowles, M.J. Pavek, R.R. Spear, C.R. Brown, B.A. Charlton, V. Sathuvalli, S. Yilma, T.L. Brandt, and N. Olsen. 2016. Targhee Russet: A high yielding dual purpose long russet with tuber soft rot resistance. *American Journal of Potato Research* 93: 189–201. https://doi.org/10.1007/s12230-016-9495-7.

Wohleb, C.H., Knowles, N.R., and M.J. Pavek. 2014. Plant Growth and Development. *In* The Potato Botany, Production and Uses, DA Navarre and MJ Pavek ed., 1st edition, CABI Press ch 5 pp. 64–82.