




Reduced Late-Season Irrigation Improves Potato Quality, Often at the Expense of Yield and Economic Return

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Abstract

With a rising global population and looming water shortages in the U.S., there is a pressing need for water-efficient farming methods. The water needs of potato plants decrease in the late season due to foliage aging and tuber maturation. Therefore, proper late-season irrigation is vital in preventing water waste and maximizing potato profits. This study assessed the feasibility of reducing late-season irrigation to improve crop water productivity (WPC), tuber quality, and economic return. Field trials were planted near Othello, WA, across three years (2018–20). Treatments included five irrigation levels (ILs), 40%, 60%, 80%, 100%, and 120% of modeled evapotranspiration (ET), and five potato cultivars: Alturas, Clearwater Russet, Ranger Russet, Russet Burbank, and Umatilla Russet. Treatments started 100 to 105 days after planting (DAP), approximately 1500 day degrees (at or near peak canopy growth), and ended at vine kill, 150 to 155 DAP. Water from reduced ILs of 40% to 80% ET was more efficiently converted into yield (WPC) for Alturas than higher ILs; however, economic return for all cultivars typically peaked when irrigation was supplied at or above 80% ET. Tuber quality generally improved with a reduction in irrigation level, occasionally at the expense of yield and economic value.

Resumen

Con el aumento de la población mundial y la inminente escasez de agua en los EE. UU., existe una necesidad apremiante de métodos agrícolas eficientes en el uso del agua. Las necesidades de agua de las plantas de papa disminuyen al final del ciclo debido al envejecimiento del follaje y la maduración de los tubérculos. Por lo tanto, el riego adecuado al final del ciclo es vital para evitar el desperdicio de agua y maximizar las ganancias de la papa. Este estudio evaluó la factibilidad de reducir el riego tardío para mejorar la productividad del agua de los cultivos (WPC), la calidad del tubérculo y el retorno económico. Los ensayos de campo se plantaron cerca de Othello, WA, a lo largo de tres años (2018-20). Los tratamientos incluyeron cinco niveles de riego (IL), 40%, 60%, 80%, 100% y 120% de evapotranspiración (ET) modelada, y cinco variedades de papa: Alturas, Clearwater Russet, Ranger Russet, Russet Burbank y Umatilla Russet. Los tratamientos comenzaron de 100 a 105 días después de la siembra (DAP), aproximadamente 1500 grados de día (en o cerca del máximo crecimiento del follaje), y terminaron con la muerte de la parte aérea, 150 a 155 DAP. El agua de IL reducidas de 40% a 80% ET se convirtió de manera más eficiente en rendimiento (WPC) para Alturas que IL más altas; sin embargo, el rendimiento económico de todas las variedades generalmente alcanzaba su punto máximo cuando el riego se suministraba al 80% o más de ET. La calidad de los tubérculos mejoró en general con una reducción en el nivel de riego, ocasionalmente a expensas del rendimiento y el valor económico.

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Introduction

In the face of an expanding global population and associated increases in demands for agricultural resources, optimizing water use efficiency in crop production has emerged as a critical challenge for sustainable food security. This urgency is underscored by the projection that by 2024, forty states across the United States anticipate encountering water shortages, as the Environmental Protection Agency reported in 2023 (U.S. Environmental Protection Agency 2022). This pressing scenario has fueled a pivot towards novel agricultural techniques that balance robust crop yields with prudent water use.

A prominent practice in this endeavor is deficit irrigation (DI) – a calculated tactic that provides crops with water below their full evapotranspiration (ET) needs, ensuring both water conservation and optimal yield and quality (Ullah et al. 2019). Illustrating the intricacies of this balance, fresh potatoes, composed of about 80% water, require substantial water throughout their growth period. In Washington State, an average potato crop's water consumption stands at roughly $7,221 \text{ m}^3 \text{ ha}^{-1}$ per season (Gonzalez et al. 2023). Given that potato yields in Washington State have averaged $70,240 \text{ kg ha}^{-1}$ over the last three years (USDA-NASS 2022), this translates to nearly 10 kg of fresh tubers per cubic meter of water.

It is noteworthy that the vast majority of previously conducted studies in the U.S. on deficit irrigation have predominantly revolved around the effects of whole-season, transitory, or a combination of sensitive growth stages of potato development and their subsequent implications on tuber yield (Essah et al. 2020; Shock et al. 1992, 1998; Pavlista 2015; Stark et al. 2013). For instance, in Colorado, Essah et al. (2020) reported that a reduction in irrigation of 20% and 30% postponed leaf aging to 86 to 90 days after planting. Their findings suggest that water consumption for these two cultivars could be lessened without compromising yield or quality. In Idaho, Stark et al. (2013) observed two medium-late maturing cultivars produce the highest yields across various drought treatments. In Nebraska, Pavlista (2015) reported a significant decrease in tuber yield when reducing irrigation between three and eight weeks after emergence. However, potato plants subjected to reduced irrigation between eight and twelve weeks after emergence did not observe a significant reduction in total yield.

While extensive research has delved into the effects of season-long and transitory deficit irrigation on potatoes, there remains a relative need for studies on the ramifications of late-season reduced irrigation on potato yield and

quality standards. The latter stages of potato production bear a crucial influence on potato development, wielding a significant impact on tuber bulking, size distribution, overall yield, and tuber quality.

Shock et al. (1992) noted that initiating reduced irrigation solely post-tuber formation can lead to water conservation. Their findings indicated that a 10% to 20% reduction in late-season irrigation did not substantially impact the yield. Similarly, Bohman et al. (2019) discerned that curtailing irrigation by 15%, based on ET during the whole season, did not markedly diminish the tuber yield. Moreover, previous research has reported increased tuber dry matter and starch content when irrigation is completely cut off or reduced during the latter part of the season (Ierna and Mauromicale 2022).

Additionally, a study conducted by Stalham (2015) evaluating deficit irrigation towards the end of the season indicated that such irrigation reduction resulted in a reduction in the incidence of growth cracks in tubers. This is significant because although tubers with growth cracks are safe to eat, their appearance makes them unsuitable for the fresh market (Storey and Davies 1992). Furthermore, when tubers are not culled from the total yield, the water use efficiency relative to production is effectively improved.

Based on these insights, we theorized that reducing irrigation at or near peak potato canopy size, approximately 1500 day degrees from planting (Doorenbos and Pruitt 1977; Wright 1981; Allen et al. 1998; Parent and Ancil 2012), would improve irrigation efficiency relative to tuber yield per amount of water applied (crop water productivity) (Rodrigues and Pereira 2009), improve tuber quality, maintain tuber yield, and maximize economic return. As potatoes transition towards full maturity after reaching full canopy cover, their water consumption undergoes a gradual reduction, coinciding with the onset of tuber bulking and maturity. This period presents an opportune window for late-season deficits, as the plants approach senescence, making such water-saving strategies more viable.

Materials and Methods

Research Site

A three-year study from 2018 to 2020 at Washington State University's (WSU) Irrigated Agriculture and Extension Center near Othello, WA, examined the effects of reduced late-season irrigation on five potato cultivars. Located at an elevation of 368 m, the research site coordinates are $46^\circ 47.453' \text{ N}$, $-119^\circ 2.513' \text{ W}$. The soil texture within the root zone, found at a depth ranging from 20 to 50 cm below the surface, was identified as Shano silt loam. The soil texture exhibited an average composition of 36% sand, 51% silt,

and 13% clay. A soil texture characterization analysis using the Soil SPAW software from the U.S. Department of Agriculture revealed that the soil had a matric bulk density of 1.45 g cm^{-3} , a saturated hydraulic conductivity of 27.23 mm d^{-1} , a saturation threshold of $0.48 \text{ m}^3 \text{ m}^{-3}$, a field capacity threshold of $0.27 \text{ m}^3 \text{ m}^{-3}$, and a permanent wilting threshold of $0.10 \text{ m}^3 \text{ m}^{-3}$ (Rawls 1998; Saxton and Rawls 2006). The upper 20 cm of the soil profile was, on average, 5% less sandy and 6% more silty than the 30 cm soil profile previously discussed.

As classified by the Koppen climate classification system, the research site's climate is Arid Steppe cold arid (BSk) (Larson and Lohrengel 2011), resulting in a ten-year average annual precipitation of 192 mm, with the summer months (April–October) receiving double the precipitation than the winter months. The region maintains an average air temperature of $10 \text{ }^\circ\text{C}$ and 66% relative humidity.

Experiment Design and Statistical Analysis

The experimental design was laid out as a split-plot design with blocks. The experiment was composed of two fields, serving as blocks, which were further segmented into five whole plots, each culminating in a total of ten whole plots across both fields. Five distinct irrigation levels (IL(s)) were randomly assigned to the whole plots in each field. Subsequently, five distinct cultivars (Cv(s)) were randomly distributed within each whole plot and replicated three times, structured using a randomized complete block design. The data was analyzed using a fixed-effect model to account for the specific effects of our primary factors of interest, such as the irrigation levels and cultivars. Secondary factors of interest, field, and year were also treated as fixed effects.

Each plot was composed of seven rows, measuring 4.3 m in length and 6.2 m in width. These rows accommodated 14 plants, with a 0.6 m alley at the end of each plot. The layout encompassed outer rows dedicated for walking, succeeded by two guard or border rows, culminating in a central data row. Notably, a red-skinned cultivar, Chieftain, was planted on each end of the plots to maintain competition for end plants and serve as a harvest marker.

The ensuing statistical analysis employed JMP Pro (version 14.5, SAS Institute Inc., Cary, NC, 1989–2019). A two-way analysis of variance (ANOVA) was executed, employing the Restricted Maximum Likelihood Method alongside the Kenward-Roger correction. This approach was adopted to scrutinize the main effects and interactions at a significance level of 0.05. The data was analyzed using a mixed-effect model to account for the specific effects of our primary factors of interest; the irrigation levels and cultivars were treated as fixed effects. A secondary factor of interest, year, was also treated as a fixed effect. The variation inherent in our experimental blocks, represented by

the two different fields and replicated subplots, were treated as random effects. Post-hoc comparisons were undertaken using the Tukey–Kramer procedure. The preference for the Tukey–Kramer procedure was grounded in its conservative nature, effectively controlling the risk of Type I errors (Lane 2010). Pearson's correlation methods were used to measure and quantify the degree and direction of linear relationships or associations between two continuous variables.

Polynomial regression analysis was used to illustrate the trend effects of the five irrigation levels on the different observations in this study. The procedure began with plotting observations against the five irrigation levels, followed by fitting a first- and second-degree polynomial regression model to the data points. The degree of polynomial was selected based on a balance between model fit and the risk of overfitting, ensuring the model's generalizability and relevance to the data structure. It is important to note that polynomial regression modeling was used as a tool for visualizing and understanding trends in the data rather than making predictive inferences. To visually represent data and results, figures and tables were created utilizing Sigmaplot (version 14.5, Systat Software, San Jose, CA) and Excel (Microsoft Corporation, Seattle, WA).

Potato Cultivars

Five russet-type potato cultivars were chosen based on their popularity and specific characteristics in the Pacific Northwest. These included:

1. Alturas, characterized as a late-maturing, high-yielding cultivar with low russetting and high tuber specific gravity (Novy et al. 2003).
2. Clearwater Russet, characterized as a fresh/processing cultivar, with medium-late maturity and relatively low concentration of reducing sugars after long-term storage (Novy et al. 2010).
3. Ranger Russet, characterized as a fresh/processing cultivar, with medium-late maturing and high resistance to *Verticillium wilt* and potato virus X (Pavek et al. 1992).
4. Russet Burbank, believed to have been released in 1902 and is a processing late-maturing cultivar (Bethke et al. 2014).
5. Umatilla Russet, characterized as a medium-late maturing processing cultivar (Mosley et al. 2000).

Irrigation Levels

The five irrigation levels (ILs) were based on modeled evapotranspiration (ET), which was estimated using the WSU's weather service (weather.wsu.edu) and weather station located 200 m north of the research site. WSU's

weather service estimated daily ET by multiplying the reference ET (ET_r) by a potato crop coefficient (Allen et al. 1998). The ET_r is computed using the ASCE Standardized Reference Evapotranspiration Equation (Allen et al. 2005), and in the case of potato, the ET_r was based on the alfalfa crop. Thus, crop coefficient (K_c) values were necessary to account for the potato crop's growth and development characteristics. Due to similarities in climate between Othello, WA, and Kimberly, ID (Larson and Lohrengel 2011), the K_c developed in Kimberly, ID, for russet potatoes were used to help estimate modeled ET (Wright 1981). The K_c values developed by Wright (1981) were converted to the three K_c stages used by the FAO-056 (Allen et al. 1998), which work with WSU's ET modeling program. The K_c values included 0.3, 0.93, 0.5 for the initial, mid-season, and late stage, respectively (<https://www.usbr.gov/pn/agrimet/cropcurves/POTAcc.html>). The initial, mid-season, and late season stages typically span between 0 to 45 (sprout dev.), 65 to 130 (tuber initiation-bulking), and 145 to 155 (maturation) days after planting (DAP), respectively. Crop coefficients for russet potatoes from Kimberly, ID, were used because there were no russet-type potato K_c values specific to the Columbia Basin.

The irrigation levels (ILs) included:

1. 120% ET: 20% more water than the ET model's recommendation, serving as a reference.
2. 100% ET: The standard recommended water amount per the ET model.
3. 80% ET: 20% less water than suggested.
4. 60% ET: 40% less water than suggested.
5. 40% ET: 60% less water than suggested.

The crop received irrigation equivalent to 100% ET from the beginning of the growing season until the initiation of the five irrigation levels (ILs). The ILs were initiated at different times: in 2018 and 2019, they began at 100 DAP, while in the 2020 growing season, they commenced at 105 DAP. These start dates coincided with peak canopy size, at approximately 1500 day degrees, calculated using the Fahrenheit scale with a base and maximum temperature of 7.2 °C and 35 °C, respectively. The ILs were terminated at vine kill, which occurred between 150 and 155 DAP over the three years.

The five ILs were administered using a lateral irrigation system (Reinke Manufacturing Co. Inc, Deshler, NE), fitted with Sprayhead sprinklers from Nelson Irrigation (Walla Walla, WA), with a relatively short throw diameter, 2.4 m, to constrain the irrigation output to its respective treatment span. Additionally, the output of each sprinkler was determined by utilizing a range of nozzle sizes and pressure regulators.

The actual discharge values from the sprinklers, responsible for replicating the desired irrigation regime, demonstrated varying degrees of success in achieving the target output. Specifically, for the 40%, 60%, 80%, and 120% ET IL, the achieved irrigation output exceeded the desired output by 2%, 2.6%, 2%, and 4.7%, respectively. The 100% ET IL closely mirrored the desired output, deviating less than 1%.

Decisions concerning the precise timing and volumetric allocation of irrigation were predicated upon the approach of the scientific irrigation scheduling method. This entailed observation of the moisture content within the soil's profile, coupled with an empirical evapotranspiration (ET) model derived from the meteorological repository of WSU's weather services (www.weather.wsu.edu) (Leib et al. 2002). From the start of the season to the start of the irrigation treatments, irrigation was scheduled to maintain the average soil water content (SWC) of the five cultivars between the soil's field capacity ($FC = 0.27 \text{ m}^3 \text{ m}^{-3}$; upper boundary) and 65% readily available water ($RAW = 0.21 \text{ m}^3 \text{ m}^{-3}$; lower boundary). By subtracting the SWC at FC from the SWC at 65% RAW and multiplying by the soil profile depth (300 mm), the allowable depletion is calculated to be 18 mm, which could sustain a matured potato crop for approximately two days (Gonzalez et al. 2023). Irrigation events were initiated when the cumulative water depletion based on ET, calculated over complete days, reached or came near 18 mm. At the time the irrigation levels were initiated, irrigation events were scheduled to maintain the mean SWC measurements, obtained from plots subjected to the 100% ET treatment, between the soil's FC and 65% RAW.

Throughout the season, SWC at depths ranging between 20 and 50 cm beneath the surface was monitored employing a neutron probe (Hydroprobe ELITE 503, Instrotek Inc., Research Triangle Park, NC). Prior to using the neutron probe at the research site, a custom SWC calibration was performed, following the instructions provided by the manufacturer of the neutron probe. Aluminum access tubes facilitated the insertion of the neutron probe into the designated measurement depths. Promptly following plant emergence, each access tube was strategically positioned between a pair of robust plants, leaving an exposed length of 30 cm to serve as the foundational base for the neutron probe. Two access tubes were installed per irrigation level in two cultivars, specifically Russet Burbank, and a second cultivar selected at random each year. We selected not to monitor SWC on the five cultivars to minimize plant damage caused by the frequent traversal to and from access tubes. Soil moisture measurements were assessed two to three times weekly. Precipitation and irrigation were monitored using a combination of automated rain gauges (TE525L, Campbell Scientific Inc., Logan, UT) and the irrigation system logs. The rain gauges were installed so the top of the funnel was 76 cm above the

ground. The total water collected from the rain gauges did not account for losses from runoff, evaporation, and deep percolation.

Furthermore, in addition to the neutron probe measurements, SWC was assessed at the conclusion of the season on the first 30 cm of soil using a ProCheck and GS3 handheld SWC probe (Metergroup, Inc., Pullman, WA). These SWC measurements were conducted across the five potato cultivars and irrigation levels, with each measurement replicated twice.

Cultural Management

In the fall, the research site was commercially fumigated for nematodes and *Verticillium* wilt in preparation for spring planting. Seed tubers were cut to weigh between 55 and 70 g and wound-healed in storage at 8.9 °C and 95% relative humidity for two to three weeks before planting. In mid-April, the seed was sowed into rows spaced 80 cm apart with 25 cm between seed pieces using a small two-row planter. The seed was planted to a depth of 20 cm by using hydraulic planting shoes and a drag-off plate. The seed was treated with fungicide during planting by spraying a solution over the seed before it was buried. Four to five weeks after planting, rows were hilled, and weeds were reduced using a Lilliston cultivator. Tubers were harvested in mid-September using a single-row harvester and held in 8.9 °C storage until further analyses.

In accordance with established agricultural norms, the trial site's nutrition and pest management adhered to esteemed grower standards. Annually, the plots received 400 kg ha⁻¹ of nitrogen (N), 250 kg ha⁻¹ of phosphorus pentoxide (P₂O₅), and 450 kg ha⁻¹ of potassium oxide (K₂O) (Lang et al. 1999). Prior to planting, the granular fertilizers were broadcasted and incorporated in 15 cm to 20 cm of soil except for N. 100 kg ha⁻¹ of N was incorporated into the soil before planting. The residual 300 kg ha⁻¹ N was applied in increments of 20 to 40 kg ha⁻¹ through the irrigation system during the vegetative growth and tuber initiation stages, spanning 40 to 105 days after planting (DAP), during the vegetative, tuber initiation, and early tuber bulking stage (Pavek et al. 2018).

Calculating Day Degrees

Utilizing an identical methodology employed by Gonzalez et al. (2023), we used weather data from WSU's weather service and a weather station positioned 200 m to the north of the research site to calculate day degrees – commonly referred to as growing degree days among potato cultivators in the Pacific Northwest – were computed. The calculation method is closely aligned with the approach outlined by

Campbell and Norman (1998). This methodology involves the derivation of day degrees based on the highest and lowest temperatures registered during a specific day, employing the subsequent equation:

$$\text{DayDegrees} = \sum_{i=1}^n \left(\frac{T_{xi} + T_{ni}}{2} - T_b \right) \Delta t$$

where:

T_{xi} signifies the maximum temperature,

T_{ni} signifies the minimum temperature,

T_b represents the base temperature,

Δt indicates the time increment of one day.

The computed day degrees are recorded as zero when the average temperature between the minimum and maximum values falls below the base temperature. The chosen base temperature, set at 7.2 °C, mirrors the standard setting adopted by other researchers for potato day degree calculations (Worthington and Hutchinson 2005).

An upper-temperature threshold of 35 °C was also introduced to align with scientific insights. This decision is underpinned by studies demonstrating a rapid decline in photosynthesis rate within potato crops as atmospheric temperatures surpass this threshold (Dwelle et al. 1981). In scenarios where the maximum temperature surpasses 35 °C, the formula above incorporates the upper-temperature threshold instead of the maximum temperature.

Calculating Crop Water Productivity

In accordance with well-established water use indicators (Rodrigues and Pereira 2009), in this investigation, the operational definition of crop water productivity (also referred to by some as water use efficiency) was defined as the ratio of the total yield achieved along the growing season and the total amount of water involved in cultivating the crop. The formulation for WP_c equation is as follows:

$$WP_c = \frac{\text{Total yield}(\text{kg ha}^{-1})}{\text{Total water applied}(\text{m}^3 \text{ ha}^{-1})}$$

Measuring Tuber Yield and Quality Metrics

Tuber quantity assessments were conducted using an automated sizing system and sorting personnel to compute

various parameters, including total yield, marketable yield, US No.1, tuber number per plant, tuber weight, distribution of tuber sizes, and the proportion of culled yield attributed to factors such as greening, growth cracks, tuber malformations, rot, and secondary growths, presented as a percentage of the total yield. These evaluations were categorized by the stipulations delineated by the USDA-Agricultural Marketing Service (1999). The categorization of the percent of US No.1, US No. 2, and culled tubers was accomplished through subjective assessment with the grade-associated size profiles subsequently verified by the automated sizer.

Tuber specific gravity was determined by employing the weight in air/(weight in air—weight in water) methodology (Kleinkopf et al. 1987). This assessment was conducted on a representative sample comprising ten tubers from the 170 g to 340 g size classification, chosen from each experimental replication.

Simultaneously, morphometric parameters and qualitative attributes were evaluated using the same subset of ten tubers. These parameters encompassed the length-to-width ratio of each tuber, susceptibility to shatter bruising, presence of stem-end discoloration, indications of blackspot bruising, a manifestation of brown center symptoms, instances of hollow heart occurrence, and the prevalence of internal brown spot defects.

Calculating Economic Value

The economic value was quantified through the utilization of the process-adjusted gross percent difference (PAGD) metric. The derivation of this metric involved a twofold process: firstly, subtracting the process-adjusted gross (PAG) value from each irrigation level (IL) from the 100% ET IL; secondly, this difference was divided by the PAG value corresponding to the 100% ET IL, followed by a multiplication by 100.

The computation of the PAG was underpinned by the use of a simulated French fry processing contract procured from the Washington State processing industry. The stipulations within this mock contract encompassed a comprehensive array of factors and assigned economic values to each treatment based on total and marketable yield, percentage of US No. 1 tubers, distribution of tuber sizes, and tuber quality in the form of specific gravity and tuber defects (Pavek et al. 2018).

Calculating Canopy Cover

The canopy cover was assessed using the ImageJ digital image analysis tool provided by the US National Institute of Health (<https://imagej.nih.gov/ij/>) as documented by Schneider et al. (2012). The imagery for this analysis originated

from high-definition aerial orthomosaics (with a resolution of 0.75 cm px⁻¹) captured throughout the growing season. The subsequent refinement of these plot images unfolded in a methodical sequence. The initial phase involved curating pertinent plot images from the designated repository. In the ensuing step, the green hue characteristic of the images was isolated using the adept threshold adjustment tool in ImageJ. The process was followed by transforming the complete image into a binary palette of black and white. Here, the previously highlighted green hue was represented as black pixels. In the culminating phase, these binary-rendered plot images underwent detailed analysis to calculate the proportion of black pixels—reflecting the green hue—within the entire image, as corroborated by Xiong et al. (2019).

Results and Discussion

The Analysis of Variance

A factorial analysis of variance (ANOVA) was employed to explore the main effects and interactions involving the factors cultivar (Cv), irrigation level (IL), and year within the dataset. Utilizing a fixed-effects model, we initially scrutinized the interaction among year, IL, and Cv, which was found to be statistically significant. Subsequently, an examination of the interaction between IL and Cv also revealed statistical significance. Consequently, we proceeded to conduct individual assessments of the main effects of IL and Cv over the three-year period. These analyses unveiled that, although a significant interaction was present in the majority of observations, the essential message and trend conveyed by the IL main effects remained consistent across the three years for each cultivar. Therefore, we opted not to delve further into the three-way interaction comprising year, IL, and Cv, as the main effect of year did not introduce meaningful variations in the interpretation of IL-related data. Additionally, an in-depth discussion of the differences between the three years would have introduced excessive and unnecessary detail and length to this already comprehensive manuscript. As a result, we treated year as a blocking term in subsequent analyses.

Moreover, the detection of a significant interaction between factors IL and Cv prompted an in-depth exploration of the underlying factors contributing to this interaction for each individual observation. The impact of IL on the observation was largely contingent upon the specific cultivar. Consequently, we conducted a thorough examination of the main effect of IL for each of the cultivars to gain a deeper understanding of this interaction's intricacies.

Weather, Day Degrees, and Canopy Cover

Over the three years of the study, minimal variability was observed among the various weather parameters. To effectively compare these multiple weather variables, we employed a reference evapotranspiration (ET_r) model, frequently referred to as potential evapotranspiration. These models are dependent on crucial weather parameters that exert a substantial influence on transpiration processes (Allen et al. 2005). To underscore the notable constancy in weather conditions over the three-year span, we conducted an evaluation of the annual ET_r for each year. In 2018, 2019, and 2020, the cumulative ET_r values throughout the potato growing season were 1314 mm, 1224 mm, and 1329 mm, respectively. The highest percent difference was recorded between 2020 and 2019, totaling 8%. Further reinforcing the consistency in weather patterns across these three years, the accumulated day degrees for the 2018, 2019, and 2020 seasons were nearly identical, with final tallies of 3050 mm, 2977 mm, and 3044 mm, respectively. Notably, between 2018 and 2020, all five potato cultivars achieved full canopy cover during the tuber bulking stage, occurring around 70 days after planting (DAP).

Total Irrigation and Precipitation

The water inputs from irrigation and precipitation assessed in each irrigation treatment differed from year to year. In 2018, the cumulative water depth received by the crop from the 120%, 100%, 80%, 60%, and 40% ET irrigation regimes was 509 mm, 552 mm, 595 mm, 638 mm, and 681 mm, respectively. In 2019, the cumulative water depth received by the crop from the 120, 100%, 80%, 60%, and 40% ET irrigation levels was 505 mm, 565 mm, 629 mm, 691 mm, and 793 mm, respectively. Finally, in 2020, the cumulative water depth received by the crop from the 120%, 100%, 80%, 60%, and 40% ET irrigation treatments was 557 mm, 625 mm, 693 mm, 761 mm, and 829 mm, respectively. Precipitation in both 2018 and 2020, after the irrigation regimes had been initiated, accounted for just 1% of the total water received by the crop during those years. In contrast, 2019 exhibited a different pattern, with non-typical rainfall contributing significantly, comprising 14% of the total water supplied to the crop. This included 17 mm of rainfall occurring approximately two weeks after the irrigation regimes were initiated and an additional 8 mm of rainfall one week before harvest.

In the present study, different nozzle sizes were used in the irrigation system to achieve the desired output for each of the five ILs. This was realized with differing levels of success. For the 40%, 60%, 80%, and 120% ET ILs, the achieved irrigation output was 2%, 2.6%, 2%, and 4.7% higher than

the desired output, respectively. The 100% ET IL closely approximated the desired irrigation output, deviating by less than 1%.

Soil Water Content

The soil water content (SWC) of potato cultivars was observed using a neutron probe to maintain uniformity within and among the ILs, aligning with the ET model's guidelines for precise irrigation scheduling. Annually, the monitoring encompassed different cultivars: Russet Burbank and Clearwater Russet in 2018, Russet Burbank and Umatilla Russet in 2019, and Russet Burbank with Ranger Russet in 2020. Late-maturing cultivars Clearwater Russet and Ranger Russet demonstrated optimal SWC values, consistently between the field capacity (FC) and 65% readily available water (RAW) throughout the season. Complementary to this, SWC was measured at the season's end—using a portable SWC probe.

An analysis of the SWC for the cultivars monitored during the three years revealed that in 2018, Clearwater Russet, at the start of the irrigation treatments, started with an average SWC of $0.22 \text{ m}^3 \text{ m}^{-3}$ across all ILs and concluded the season with values of $0.24 \text{ m}^3 \text{ m}^{-3}$, $0.23 \text{ m}^3 \text{ m}^{-3}$, $0.22 \text{ m}^3 \text{ m}^{-3}$, $0.19 \text{ m}^3 \text{ m}^{-3}$, and $0.17 \text{ m}^3 \text{ m}^{-3}$ corresponding to ILs 120%, 100%, 80%, 60%, and 40% ET, respectively. Concurrently, Russet Burbank commenced with $0.23 \text{ m}^3 \text{ m}^{-3}$, with season-end measurements of $0.37 \text{ m}^3 \text{ m}^{-3}$, $0.35 \text{ m}^3 \text{ m}^{-3}$, $0.34 \text{ m}^3 \text{ m}^{-3}$, $0.33 \text{ m}^3 \text{ m}^{-3}$, and $0.33 \text{ m}^3 \text{ m}^{-3}$ for the same ILs.

In 2019, Umatilla Russet began with an average SWC of $0.25 \text{ m}^3 \text{ m}^{-3}$. At the season's conclusion, the SWC values were $0.28 \text{ m}^3 \text{ m}^{-3}$, $0.26 \text{ m}^3 \text{ m}^{-3}$, $0.25 \text{ m}^3 \text{ m}^{-3}$, $0.24 \text{ m}^3 \text{ m}^{-3}$, $0.23 \text{ m}^3 \text{ m}^{-3}$ for ILs 120%, 100%, 80%, 60%, and 40% ET, respectively. The SWC observed in Russet Burbank for the same ILs were $0.36 \text{ m}^3 \text{ m}^{-3}$, $0.34 \text{ m}^3 \text{ m}^{-3}$, $0.34 \text{ m}^3 \text{ m}^{-3}$, $0.33 \text{ m}^3 \text{ m}^{-3}$, and $0.32 \text{ m}^3 \text{ m}^{-3}$. Russet Burbank's season started with a SWC of $0.23 \text{ m}^3 \text{ m}^{-3}$.

Finally, in 2020, Ranger Russet's SWC at the start of the irrigation treatments was at $0.23 \text{ m}^3 \text{ m}^{-3}$, which, by season's end, increased to $0.24 \text{ m}^3 \text{ m}^{-3}$, $0.23 \text{ m}^3 \text{ m}^{-3}$, $0.20 \text{ m}^3 \text{ m}^{-3}$, $0.18 \text{ m}^3 \text{ m}^{-3}$, and $0.16 \text{ m}^3 \text{ m}^{-3}$ corresponding to irrigation treatments 120%, 100%, 80%, 60%, and 40% ET, respectively. The SWC of Russet Burbank at the start of the season was $0.23 \text{ m}^3 \text{ m}^{-3}$, which ballooned at end of the season to $0.33 \text{ m}^3 \text{ m}^{-3}$, $0.32 \text{ m}^3 \text{ m}^{-3}$, $0.31 \text{ m}^3 \text{ m}^{-3}$, $0.31 \text{ m}^3 \text{ m}^{-3}$, and $0.30 \text{ m}^3 \text{ m}^{-3}$ for the same ILs (Fig. 1; Table 1).

Irrigation was scheduled based on the average evapotranspiration of the five potato cultivars, aiming to maintain the SWC within the soil's FC and 65% of the readily available water. Additionally, irrigation scheduling decisions also took into account the average SWC from the two potato cultivars

Fig. 1 Soil water content measurements collected throughout the seasons in 2018, 2019, and 2020 from plots subjected to 100% ET irrigation level for two cultivars as a function of days after planting

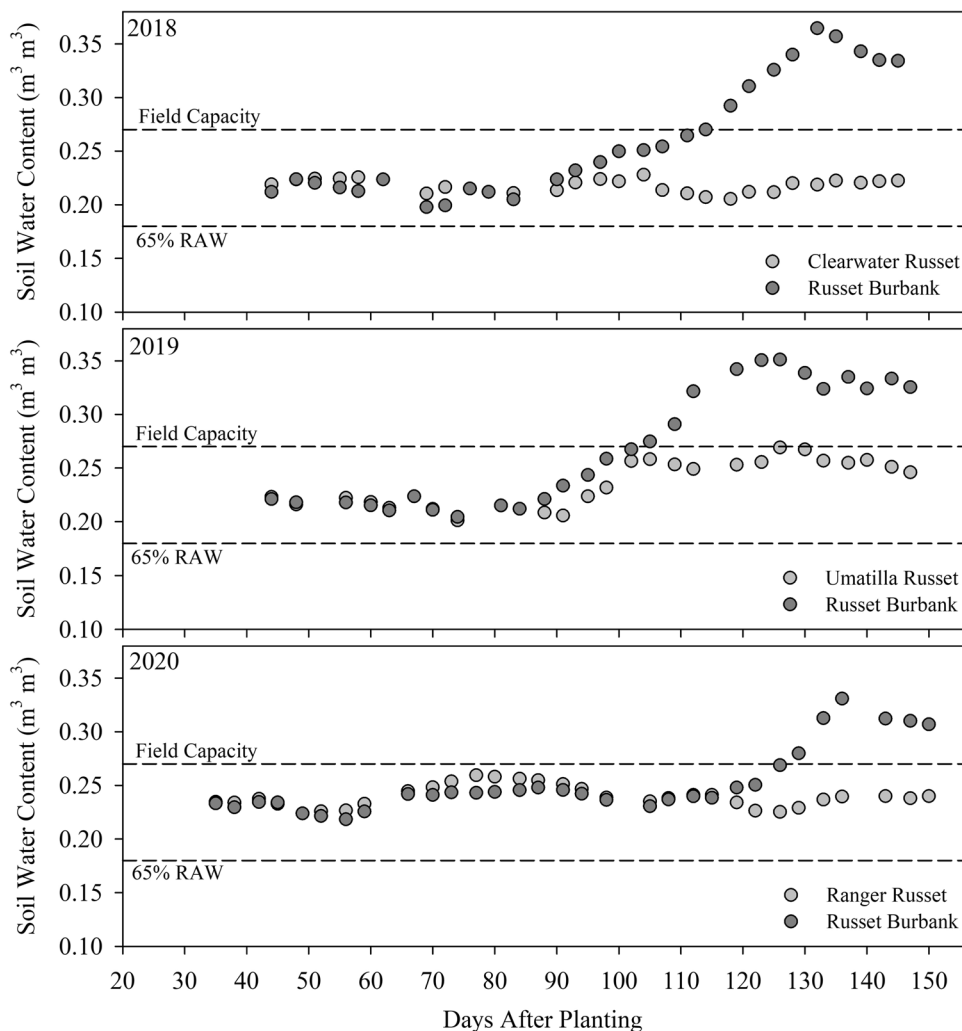


Table 1 Soil water content means collected at the end of the season in 2018, 2019, and 2020 from each irrigation level and two potato cultivars

Level	2018		2019		2020	
	Clearwater Russet	Russet Burbank	Umatilla Russet	Russet Burbank	Ranger Russet	Russet Burbank
$m^3 m^{-3}$						
120% ET	0.244	0.369	0.277	0.355	0.241	0.325
100% ET	0.231	0.354	0.261	0.342	0.226	0.317
80% ET	0.222	0.339	0.25	0.336	0.204	0.308
60% ET	0.193	0.332	0.235	0.329	0.183	0.308
40% ET	0.165	0.327	0.229	0.324	0.161	0.304

Field capacity = $0.27 m^3 m^{-3}$

65% Readily Available Water = $0.18 m^3 m^{-3}$

growing using irrigation level 100% ET. However, since the five potato cultivars were planted along the path of the lateral irrigation system, personalized irrigation events were not possible; the five potato cultivars received the same quantity of irrigation.

Despite receiving an equivalent volume of irrigation, particular distinctions in SWC profiles emerged among the cultivars. While Alturas, Clearwater Russet, Ranger Russet, and Umatilla Russet preserved their SWC within the desired range, Russet Burbank’s SWC exceeded the soil’s

FC, notably after 120 DAP in 2018, 105 DAP in 2019, and 130 DAP in 2020. This deviation suggests that Russet Burbank's hydration requirements late in the season are relatively subdued, especially when compared with its counterparts: Clearwater Russet in 2018, Umatilla Russet in 2019, and Ranger Russet in 2020. We infer that this unique soil water consumption trend in Russet Burbank might stem from its relatively earlier senescence than other cultivars.

Furthermore, the elevated SWC in Russet Burbank towards the latter part of the season could potentially negate the discernible effects of the irrigation treatments. Subsequent research endeavors to assess these cultivars with different water requirements should consider an irrigation system that can account for the potato cultivar's water requirements. In a complementary approach, the experimental design might be structured in such a manner as to facilitate the individualized irrigation of each potato cultivar.

Process Adjusted Gross Percent Difference Response to Reduced Late-Season Irrigation

The mean process-adjusted gross percent difference (PAGD) among the five ILs were significantly different for Alturas ($p=0.0001$), Clearwater Russet ($p<0.0001$), Ranger Russet ($p<0.0001$), Russet Burbank ($p=0.0223$), and Umatilla Russet ($p<0.0001$). In the case of Alturas, the reduction in late-season irrigation by 20% and 40% from 100% ET did not have a significant impact on PAGD. However, a more substantial 60% reduction from 100% ET in late-season irrigation resulted in a significant 19% decrease in PAGD. Conversely, increasing irrigation by 20%, from 100% ET, beyond the recommended ET model levels led to a 17% reduction in PAGD. No significant differences were observed in PAGD among the 60% ET, 80% ET, and 100% ET treatments. Similarly, Umatilla Russet exhibited no significant decrease in PAGD with a 20% reduction in late-season irrigation. However, a 40% reduction in late-season irrigation did lower PAGD by 14%, and an additional 20% reduction resulted in an extra 16% reduction in PAGD. While not statistically significant, irrigating with an additional 20% water, exceeding the ET model recommendation, led to a 12% decrease in PAGD (Fig. 2).

In contrast, Clearwater Russet experienced a substantial reduction in PAGD as late-season irrigation was curtailed. Reductions of 20%, 40%, and 60% from 100% ET in late-season irrigation corresponded to significant decreases in PAGD by 9%, 26%, and 38%, respectively. Interestingly, providing additional irrigation beyond the ET model recommendation did not yield a significant improvement in Clearwater Russet's PAGD (Fig. 2).

For Ranger Russet, PAGD exhibited a significant decrease when late-season irrigation was reduced by a minimum of 40% from 100% ET, resulting in a 13% loss in PAGD. An

additional 20% reduction in late-season irrigation led to an additional 13% loss. Similar to Clearwater Russet, Ranger Russet did not show a significant improvement in PAGD with additional irrigation beyond the ET model recommendation. In the case of Russet Burbank, PAGD appeared to be less affected by reductions in late-season irrigation compared to the other four cultivars. The only significant reduction in PAGD was observed when late-season irrigation was reduced by 60% from 100% ET, resulting in an 18% loss in PAGD. Interestingly, no significant improvement in PAGD was observed, with a 20% increase in late-season irrigation.

Notably, four potato cultivars did not observe a decline in PAGD following a 20% reduction in late-season irrigation. Three of the five cultivars observed a significant decline in PAGD following a 40% reduction in late-season irrigation. However, all the cultivars observed a significant decline in PAGD following a 60% reduction in late-season irrigation. Additionally, over-irrigating with 120% ET did not prove to be a good practice. The five potato cultivars' PAGD did not significantly benefit from the additional 20% more irrigation. Over-irrigation at 120% ET led to a significant decline in tuber quality in Alturas and a numerical and visual decline in Umatilla Russet (Fig. 2).

A deeper examination of Alturas' PAGD improvement following a reduction in late-season irrigation revealed significant enhancements across various parameters, including average tuber number per plant, specific gravity, size distribution, and percent of US No.1 tubers. These improvements were achieved through more conservative irrigation practices late in the season. Notably, optimizing desired tuber sizes (113 g to 340 g), achieving an ideal tuber specific gravity, and maximizing US No.1 yield were key outcomes that improved PAGD and saved irrigation water. Alturas' PAGD was further improved by a notable reduction in tuber growth cracks and an increase in total yield, directly resulting from a 20% reduction from 100% ET in late-season irrigation. The mentioned parameters will be discussed ahead.

The limited effectiveness of varying ILs on Russet Burbank's PAGD may be linked to the notable disparity in soil water content (SWC) observed at the end of the season. Across the three years and ILs, Russet Burbank's average SWC was 50% higher than the mean SWC of the other monitored cultivars, which averaged 33% (Fig. 1). Given that the SWC of Russet Burbank exceeded the soil's field capacity across the five ILs, the impact of the lower ILs on PAGD was negated, as these lower ILs failed to deliver a significant reduction in late-season irrigation.

Total Yield Response to Reduced Late-Season Irrigation

Across the five ILs, Clearwater Russet stood out in 2020 by achieving the highest total yield among the five cultivars,

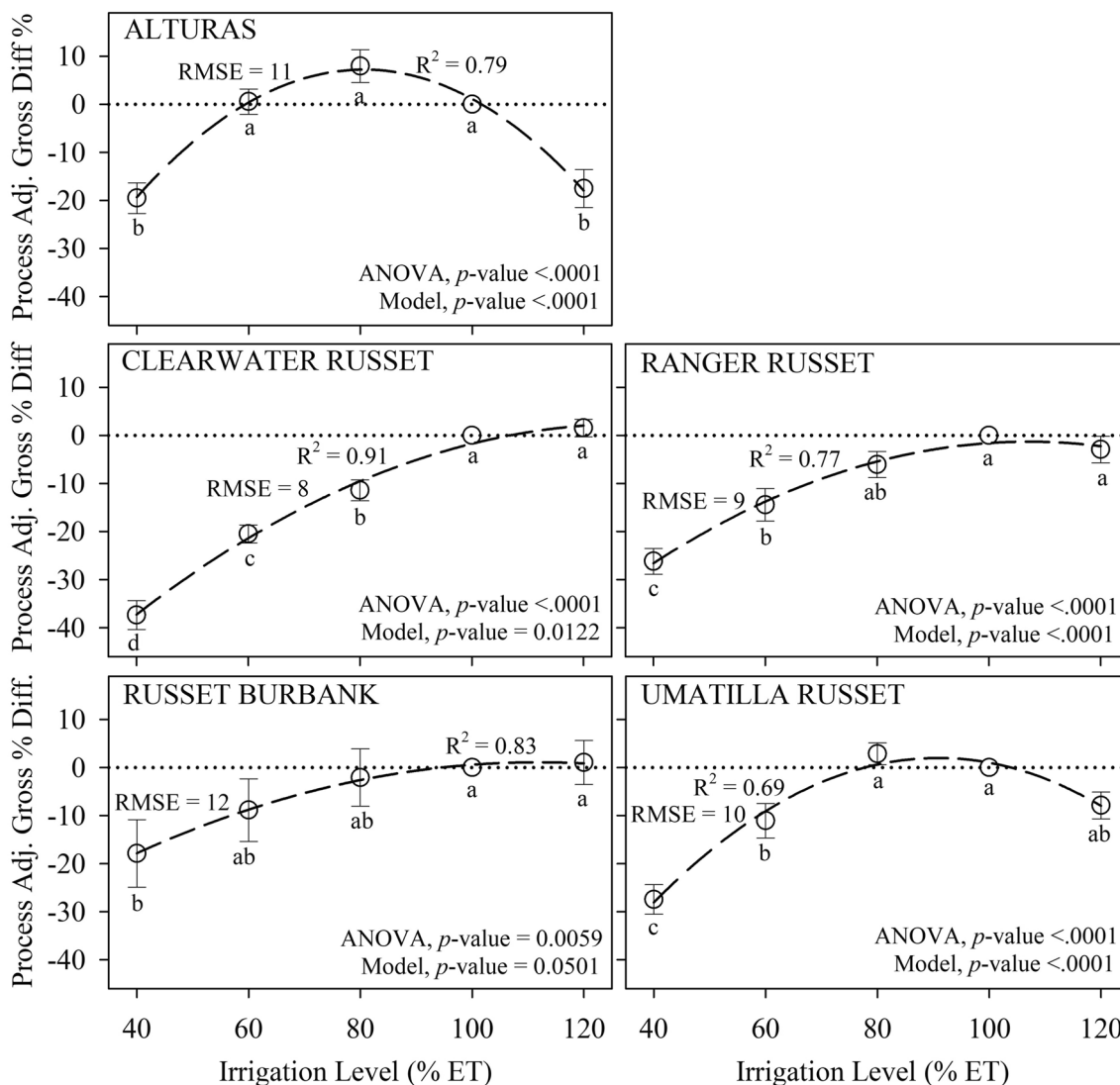


Fig. 2 Analysis of variance, post-hoc comparison, and best fit curve analysis of the mean process adjusted gross % difference from 100% ET irrigation level for each of five irrigation levels and five potato cultivars, averaged across three years (2018–20). The error bars are

standard error. For each irrigation level, processed adjusted gross with different letters is significantly different. The analysis of variance was conducted with a significance level of 0.05

averaging 125.9 MT ha⁻¹. This was significantly higher than the yields observed in 2019 (98.05 MT ha⁻¹) and 2018 (94.62 MT ha⁻¹) ($p=0.0031$). When comparing the mean total yield values among the five ILs, significant differences were found in Alturas ($p<0.0001$), Clearwater Russet ($p<0.0001$), Ranger Russet ($p<0.0001$), Russet Burbank ($p<0.0001$), and Umatilla Russet ($p<0.0001$). Overall, reducing late-season irrigation negatively impacted the total yield for the five potato cultivars. In the case of Clearwater Russet and Russet Burbank, each reduction in IL corresponded to a decrease in total yield of 10.2 MT ha⁻¹ and 7.1 MT ha⁻¹, respectively (Fig. 3).

While Clearwater Russet and Russet Burbank both exhibited a significant linear decrease in total yield with

each IL reduction, there were instances where the ILs showed no statistically significant differences. Specifically, in the case of Clearwater Russet, although there was a notable reduction in total yield when late-season irrigation was reduced by 20% from 100% ET, this decline did not reach statistical significance. The same trend was observed when irrigation decreased from 80 to 60% ET (Fig. 3).

For Alturas and Umatilla Russet, there were no significant differences in total yield when irrigating at 120%, 100%, and 80% ET late in the season. In these cases, reducing late-season irrigation by 20% also did not lead to a significant decline in total yield. Furthermore, irrigating with 20% more water than the recommended 100% ET did not result in a statistically significant increase in total

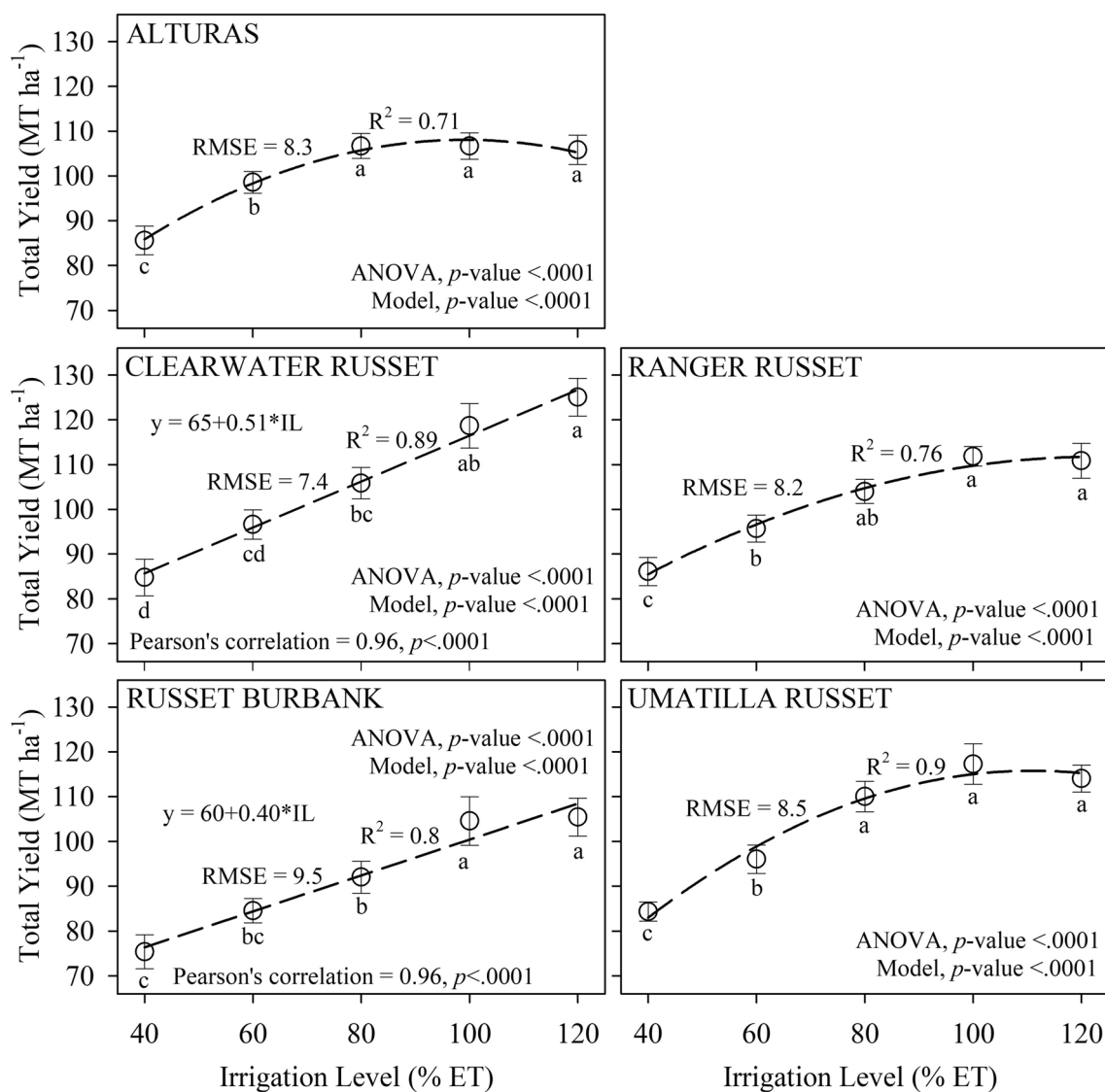


Fig. 3 Analysis of variance, post-hoc comparison, and best fit curve analysis of the mean total yield as influenced by five irrigation levels for five potato cultivars, averaged across three years (2018–20). The

error bars are standard error. For each irrigation level, total yield with different letters is significantly different. The analysis of variance was conducted with a significance level of 0.05

yield. However, a 40% reduction in late-season irrigation resulted in a significant 7% total yield loss in Alturas and 18% in Umatilla Russet. In the case of Ranger Russet, a 20% reduction from 100% ET in late-season irrigation resulted in a significant 7% total yield loss. Additional irrigation reduction from 100% ET late-season irrigation resulted in significantly lower total yields.

Similarly to the other potato cultivars, irrigating with an additional 20% from 100% ET did not improve total yield. All five potato cultivars experienced a statistically significant decrease in total yield following a 40% and 60% reduction from 100% ET in late-season irrigation. This highlights the risks associated with substantial reductions in late-season

irrigation, emphasizing the importance of avoiding excessive cutbacks in water supply during this period (Fig. 3).

This study demonstrates that for Alturas and Umatilla Russet, optimizing total yield is achievable by implementing irrigation at ILs ranging from 80 to 100% ET late in the season. This approach efficiently maintains yield without significant loss while concurrently facilitating water conservation. Further analysis, incorporating post-hoc comparison and regression techniques, elucidates that exceeding the ET model's recommendation by 20% proves to be detrimental to yield optimization. This assertion is corroborated by the findings of Crosby and Wang (2021). Particularly notable is the observation that in cultivars such as Alturas, Ranger

Russet, Russet Burbank, and Umatilla Russet, there is either stagnation or decline in total yield when subjected to this excessive irrigation (Fig. 3).

In the case of Alturas Ranger Russet., Russet Burbank, and Umatilla Russet, we surmise that the potential total yield increase associated with irrigating with 120% ET was offset by the concurrent rise in field tuber-rot, attributed to elevated soil moisture levels. Given the inherent propensity of deteriorating tubers to be excluded by the harvester's conveyers, a plausible scenario exists wherein these tubers were omitted from the final count. Potato yield losses in response to a reduction in irrigation were in agreement with the empirical findings of esteemed studies such as those by Cappaert et al. (1992), Shock et al. (1998), and Yuan et al. (2003). This supports the possibility of adopting late-season reduced irrigation for growing potatoes, saving water resources without compromising yields. Our findings align with those reported by Crosby and Wang (2021).

However, it is essential to note that certain cultivars like Clearwater Russet and Russet Burbank experienced a consistent yield decline with every irrigation reduction. Thus, growers need to calibrate their irrigation strategies based on specific cultivars. These findings are consistent with established research, reinforcing the importance of precise irrigation management in potato farming.

Market Yield Response to Reduced Late-Season Irrigation

The market yield means among the five ILs were significantly different on Alturas ($p < 0.0001$), Clearwater Russet ($p < 0.0001$), Ranger Russet ($p < 0.0001$), Russet Burbank ($p = 0.0029$), and Umatilla Russet ($p < 0.0001$). In general, reducing late-season irrigation led to a decrease in market yield. For Clearwater Russet, Ranger Russet, Russet Burbank, and Umatilla Russet, reducing late-season irrigation by 20% from 100% ET did not result in a statistically significant loss in market yield (Fig. 4).

However, a 40% reduction from 100% ET resulted in a significant market yield loss of 21% for Clearwater Russet, 12% for Ranger Russet, 17% for Russet Burbank, and 16% for Umatilla Russet. Additionally, increasing irrigation by an additional 20% from the recommended 100% ET did not result in a significant increase in market yield for Clearwater Russet, Ranger Russet, Russet Burbank, and Umatilla Russet. In fact, the market yield between the 100% and 120% ET treatments could be categorized as a plateau when analyzing using the non-linear fitted model. In the case of Alturas, reducing late-season irrigation by 20% and 40% from 100% ET did not result in a significant market yield loss. However, reducing late-season irrigation by 60% from 100% ET

resulted in a statistically significant 17% loss in market yield. Importantly, the market yields for 100%, 80%, and 60% ET were not significantly different, as illustrated by the post-hoc comparison (Fig. 4).

This study demonstrated that it is possible to cut back irrigation late in the season, maintain market yield, and save water. The results from this study are in agreement with the results of Essah et al. (2020), who reported no significant difference in marketable yield following a 10% and 15% reduction in irrigation water late in the season.

Percent US No.1 Yield Response to Reduced Late-Season Irrigation

The percent of US No.1 tubers means among the five ILs were significantly different on Alturas ($p = 0.0001$), Clearwater Russet ($p < 0.0001$), Ranger Russet ($p < 0.0001$), Russet Burbank ($p = 0.0008$), and Umatilla Russet ($p < 0.0001$). The reduction of late-season irrigation produced mixed results across the five potato cultivars. For Alturas, Russet Burbank, and Umatilla Russet, the reduction in late-season irrigation led to an increase in the percentage of US No.1 tubers. Specifically, reducing late-season irrigation by at least 40% from 100% ET in Alturas resulted in a 10% gain in the percentage of US No.1 tubers. In the case of Russet Burbank, a 60% reduction from 100% ET produced a significant 11% gain in the percentage of US No.1 tubers. For Umatilla Russet, a 20% reduction from 100% ET also resulted in a significant gain of 5% in the percentage of US No.1 tubers. For Alturas and Umatilla Russet, there was no significant difference between the percentage of US No.1 tubers when late-season irrigation was reduced by 60% and 40% from 100% ET (Fig. 5).

In contrast, reducing late-season irrigation in Clearwater Russet and Ranger Russet led to a loss in the percentage of the US No.1 tubers. Reducing late-season irrigation by at least 40% from 100% ET resulted in a loss of 6% for Clearwater Russet and 4% for Ranger Russet. These findings are in direct agreement with the findings of Hang and Miller (1986). Irrigating with an additional 20% more water than the 100% ET, recommended by the ET model did not significantly change the percentage of US No.1 tubers for the five potato cultivars (Fig. 5).

US No.1 tubers represent the highest quality in potatoes, making it crucial for potato growers to optimize their irrigation strategies to maximize the yield of said tuber category. In general, these findings underscore that reducing late-season irrigation has the potential to increase the percentage of US No.1 tubers for some cultivars.

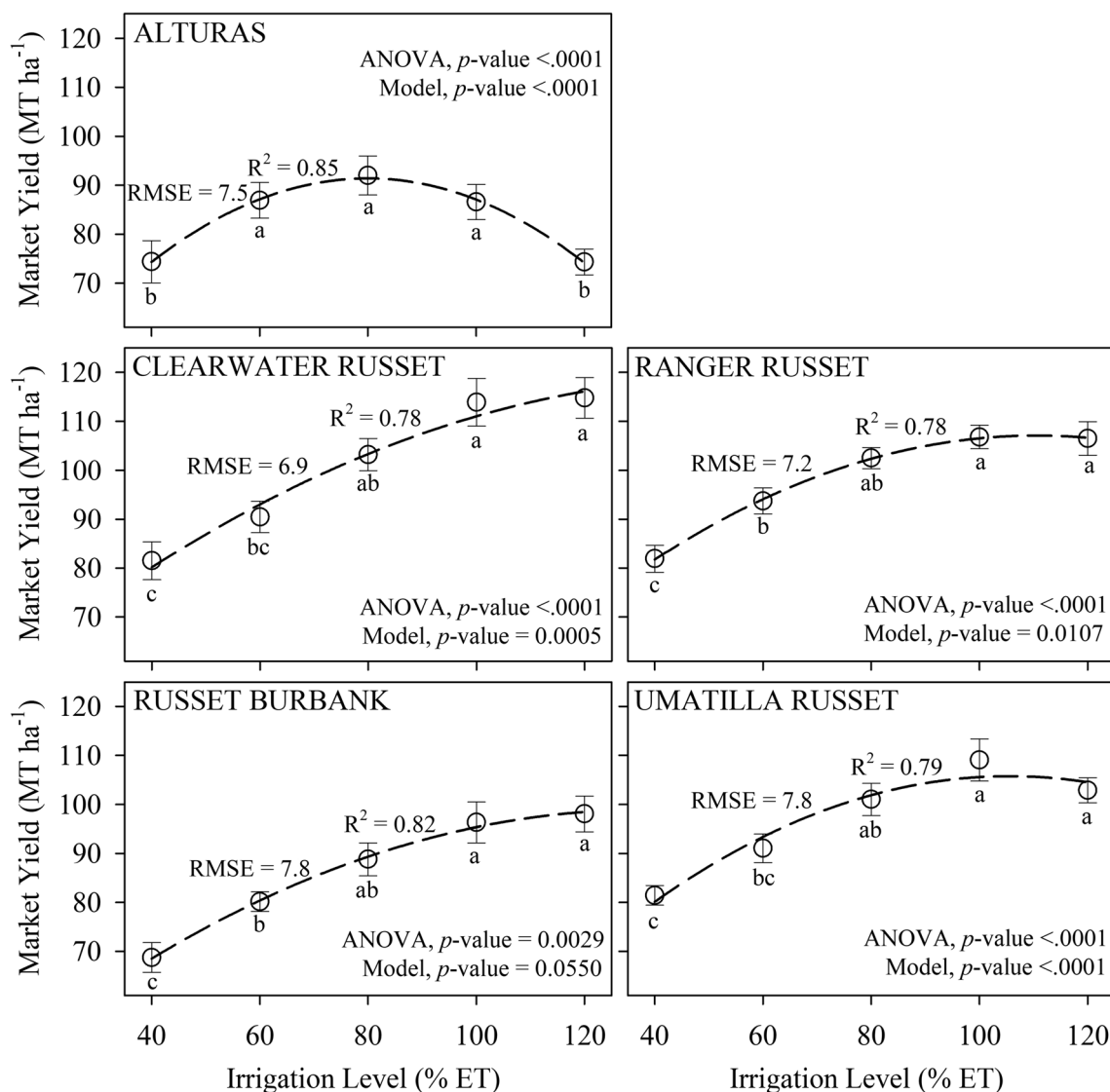


Fig. 4 Analysis of variance, post-hoc comparison, and best fit curve analysis of the mean market yield as influenced by five irrigation levels for five potato cultivars, averaged across three years (2018–20). The error bars are standard error. For each irrigation level, market

yield with different letters is significantly different. The analysis of variance was conducted with a significance level of 0.05. Market yield accounts for US No.1, 2s, and tubers > 113 g

Crop Water Productivity Response to Reduced Late-Season Irrigation

The mean crop water productivity values (WP_c) among the five ILs were found to be significantly different on potato cultivars: Alturas ($p < 0.0001$) and Umatilla Russet ($p < 0.0001$). The reduction of late-season irrigation did not significantly affect the WP_c for four of the five cultivars. For Alturas, reducing late-season irrigation by 20% from 100% ET resulted in an 8% increase in WP_c . Further reduction in late-season irrigation did not significantly change WP_c (Fig. 6). These findings align with the noted results

in WP_c when reducing irrigation, as reported by previous studies (Stark et al. 2013; Akkamis and Caliskan 2023). In the case of Umatilla Russet, reducing late-season irrigation did not result in significant improvements in WP_c . Additionally, there was no significant difference in WP_c among the four lower ILs. However, irrigating with an additional 20% irrigation greater than the recommended by the 100% ET resulted in a 10% reduction in the WP_c for both Alturas and Umatilla Russet. The substantial decrease in WP_c observed in both Alturas and Umatilla Russet when applying an irrigation regimen that exceeded the recommended ET model by 20% was attributed to the absence of

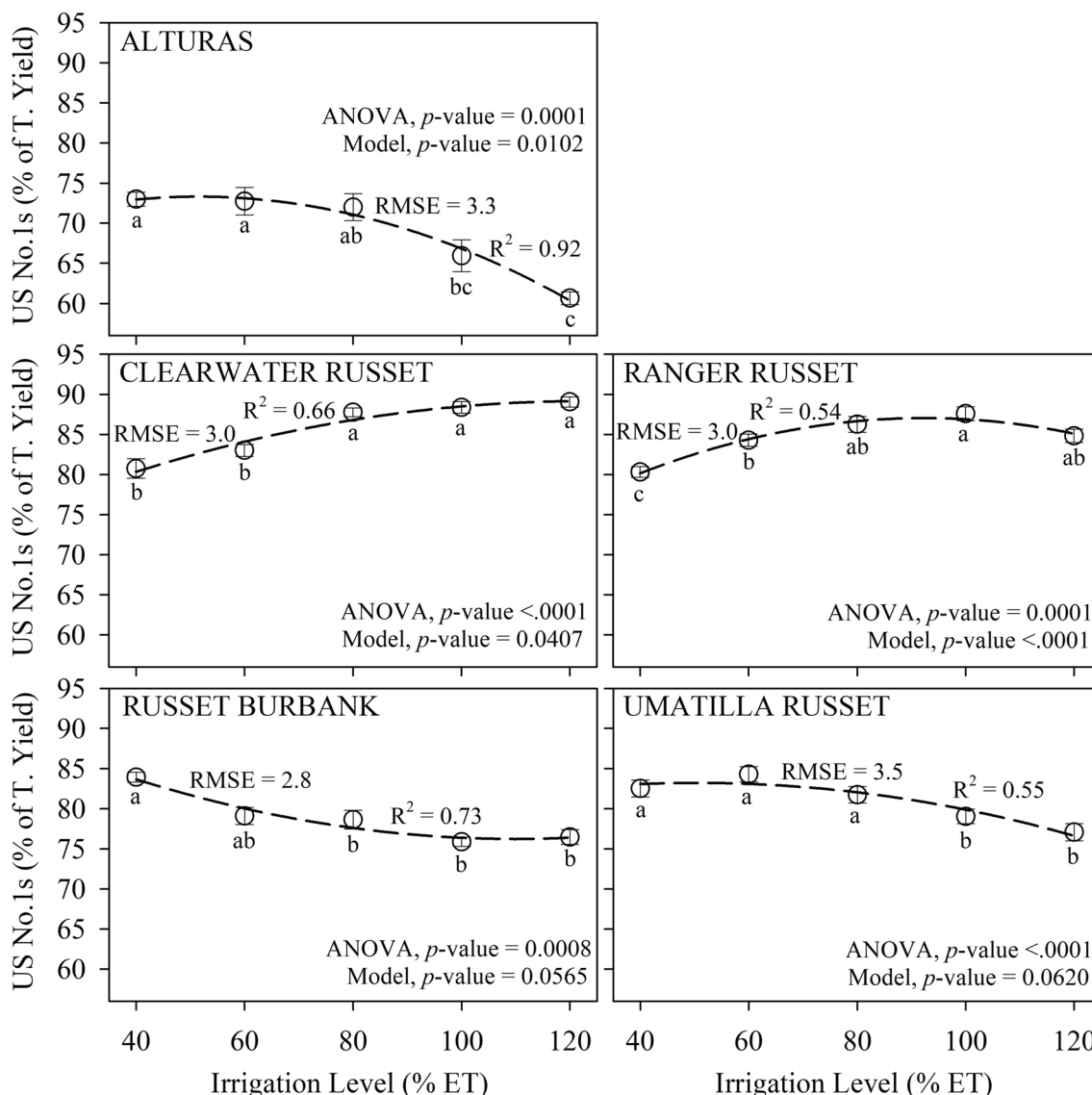


Fig. 5 Analysis of variance, post-hoc comparison, and best fit curve analysis of the mean percentage of US No.1 tubers as influenced by five irrigation levels for five potato cultivars, averaged across three years (2018–20). The error bars are standard error. For each irriga-

tion level, US No.1 yield with different letters is significantly different. The analysis of variance was conducted with a significance level of 0.05. Percent of US No.1 s tubers is comprised of tubers weighing > 113–576 g without external defects

any corresponding increase in total yield. Surprisingly, the additional water added to the crop did not result in a higher total yield (Fig. 6).

The WP_c among the five potato cultivars irrigated with the 100% ET regimen was significantly different ($p < 0.0001$). When examining the WP_c of the cultivars irrigated with 100% ET, the highest WP_c was achieved by Clearwater Russet and Umatilla Russet, averaging 16.6 kg m^{-3} . This was followed by Alturas with 15.9 kg m^{-3} . The lowest WP_c was achieved by Russet Burbank with 14.6 kg m^{-3} (Fig. 7), which agrees with the reported findings of Stark et al. (2013).

Tuber Weight Response to Reduced Late-Season Irrigation

The mean tuber weight values among the five ILs were found to be significantly different on potato cultivars: Alturas ($p < 0.0001$), Clearwater Russet, ($p < 0.0001$), Ranger Russet ($p = 0.0047$), Russet Burbank ($p = 0.00506$), and Umatilla Russet ($p = 0.0056$). There is a discernible trend of diminishing mean tuber weight across the five potato cultivars as the late-season irrigation is reduced from 100% ET (Fig. 8), aligning with similar studies conducted in the past (Onder et al. 2005; Aliche et al. 2018).

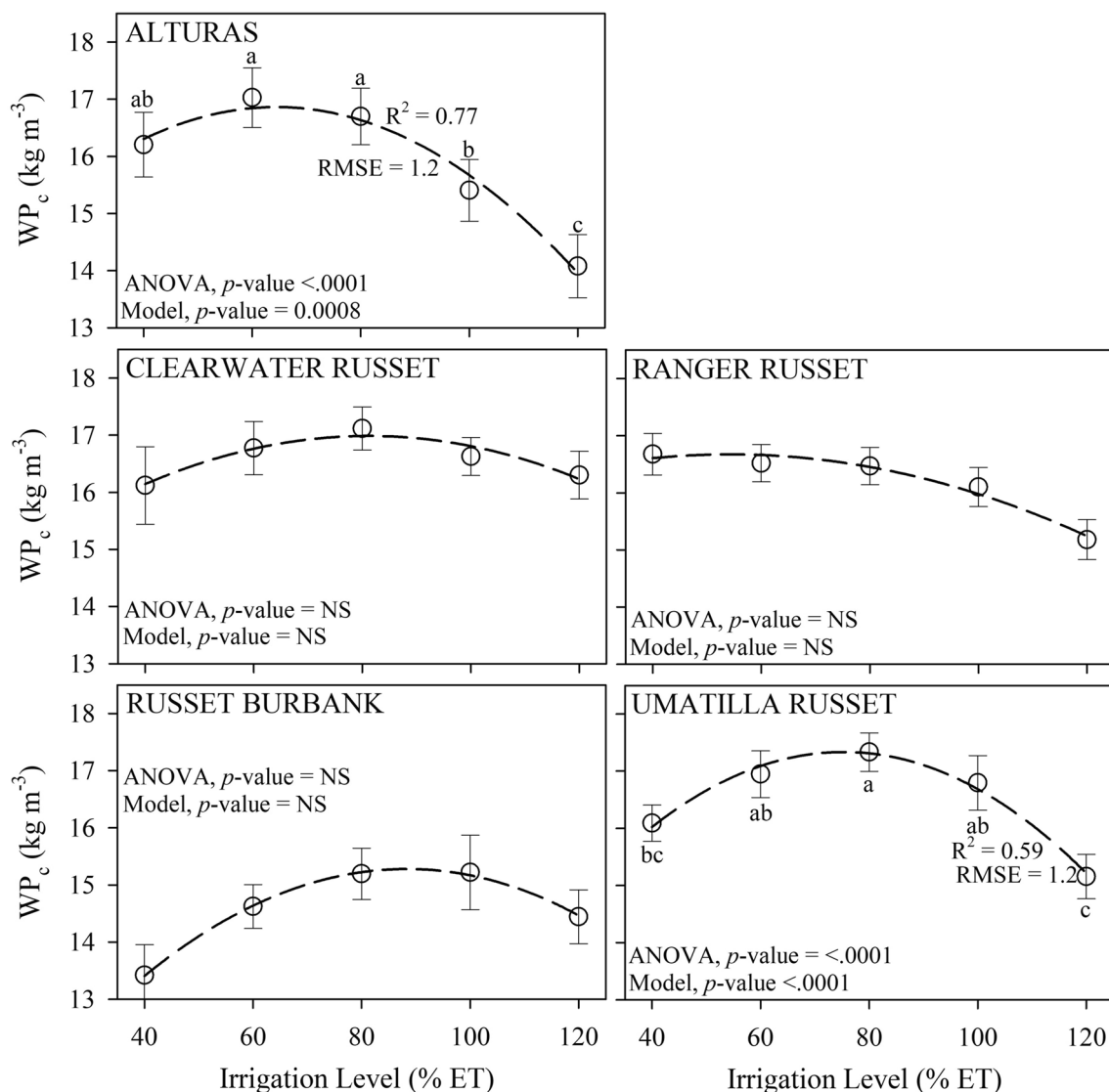


Fig. 6 Analysis of variance, post-hoc comparison, and best fit curve analysis of the mean crop water productivity (WP_c =total yield/total water applied) as influenced by five irrigation levels for five potato cultivars, averaged across three years (2018–20). The error bars are

standard error. For each irrigation level, WP_c with different letters is significantly different. The analysis of variance was conducted with a significance level of 0.05. The dotted line represents the mean WP_c among the five cultivars and irrigation levels

However, after a closer examination of Alturas and Clearwater Russet, a significant decline in tuber weight only occurs after at least a 40% reduction from 100% ET in late-season irrigation. The mean tuber weight from ILs 40% and 60% ET are not significantly different for both Alturas and Clearwater Russet. In the case of Ranger Russet and Umatilla Russet, a significant decline in the mean tuber weight is only possible after reducing late-season irrigation by 60% from 100% ET, which resulted in a mean tuber weight loss of 17% for Ranger Russet and a 20% loss for Umatilla Russet. Meanwhile, Russet Burbank exhibits a significant negative linear relationship between mean tuber weight and the five irrigation levels (Pearson's correlation=0.53; $p < 0.001$),

indicating that each additional IL reduced late in the season resulted in a mean tuber weight loss of 14%. However, the post-hoc comparison revealed no significant difference in the mean tuber weight among the four lowest irrigation levels in Russet Burbank. Lastly, there was no significant difference in the mean tuber weight among the top three irrigation levels across the five potato cultivars (Fig. 8).

Tuber Number per Plant Response to Reduced Late-Season Irrigation

The mean tuber number per plant values (TNPP) were not expected to change with a reduction in late-season

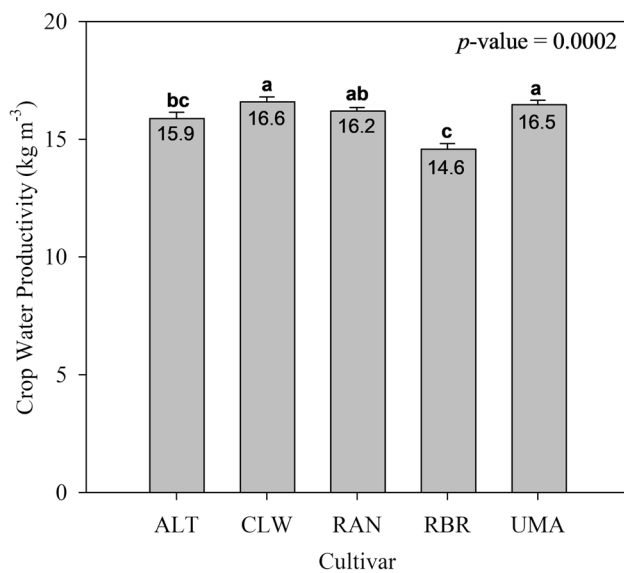


Fig. 7 Analysis of variance and post-hoc comparison of the mean crop water productivity among the five potato cultivars. Values averaged across data from three years (2018–20)

irrigation since the ILs were applied several weeks after tuber initiation. Interestingly, Alturas' TNPP among the five ILs was significantly different ($p = 0.0047$). In this instance, reducing late-season irrigation led to a higher TNPP. Alturas produced the highest TNPP following a 40% reduction in late-season irrigation, as indicated by the post-hoc comparison. Similar findings were observed by Onder et al. (2005), where irrigation levels of 66% and 33% from full evapotranspiration resulted in higher TNPP. In contrast, Karafyllidis et al. (1996) reported a significant decrease in TNPP when irrigation was reduced during the tuber formation stage. Moreover, this study found that irrigating with an additional 20% more water than 100% ET late in the season resulted in a significant decrease in TNPP in Alturas (Fig. 9).

Tuber Specific Gravity Response to Reduced Late-Season Irrigation

The tuber specific gravity means among the five ILs were significantly different for Alturas ($p < 0.0001$), Clearwater Russet ($p < 0.0001$), Ranger Russet ($p < 0.0001$), Russet Burbank ($p < 0.0001$), and Umatilla Russet ($p < 0.0001$). Tuber specific gravity for all cultivars increased linearly as late-season irrigation was reduced for the five potato cultivars, aligning with findings reported in previously published studies (Guenel and Karadogan 1998; Yuan et al. 2003; Stark et al. 2013). For Alturas, Clearwater Russet, Ranger Russet, Russet Burbank, and Umatilla Russet, each reduction in IL increased tuber specific gravity by 0.0061,

0.0033, 0.0016, 0.0010, and 0.0033, respectively. On a parallel note, the tuber specific gravity of Russet Burbank and Ranger Russet exhibited a notable insensitivity to alterations in the five ILs, with an average slope registering a 40% decrease compared to the remaining three cultivars (Fig. 10).

The frozen French fry industry in the Pacific Northwest prefers tuber specific gravity between 1.084 and 1.086. The present study achieved this optimal range by reducing late-season irrigation by 30%, 10%, 60%, and 30% on Alturas, Clearwater Russet, Ranger Russet, and Umatilla Russet, respectively, based on the curvilinear trends fitted on the data. Russet Burbank's tuber specific gravity among the five ILs remained below the threshold of 1.080 (Fig. 10). It is worth emphasizing that improper management of reduced irrigation carries the risk of causing excessively high tuber specific gravity.

Prior scientific investigations have commonly attributed the occurrence of tuber growth cracks to fluctuating environmental conditions, including soil moisture, temperature, and tuber growth vigor (Jefferies and MacKerron 1987; Hiller and Thornton 2008). In the present study, Alturas irrigated with 100% ET late in the season developed a tuber growth crack incidence of 24%, compared to the near 5% observed when irrigated with the 40% ET IL, revealing a 19% reduction in tuber growth crack incidence by reducing irrigation by 60% late in the season (Fig. 10). Since the deficit irrigation levels started after 100 DAP, in disagreement with previous studies (Jefferies and MacKerron 1987; Hiller and Thornton 2008), these findings indicate that most growth cracks in Alturas occurred during the last eight weeks before harvest. Most importantly, these findings indicate that growth cracks can be mitigated with proper soil–water management late in the season.

Tuber specific gravity is one of the essential factors in frozen processed potatoes; thus, having a simple management method for modifying tuber specific gravity before harvest would be a noteworthy advancement. Our findings indicate that tuber specific gravity can be modified by reducing irrigation eight weeks before harvesting. These findings are supported by Hang and Miller (1986) and Shock et al. (1998). They reported a slight increase in tuber specific gravity when reducing irrigation in the latter part of the season. In our findings, the increase in tuber specific gravity was proportional to the deficit level; the more significant the reduction in irrigation, the higher the response. We hypothesize that the perceived gradual water loss by the crop late in the season triggered a gradual maturation response, reducing photosynthesis and sugar translocation and speeding up starch synthesis in tubers. Although this assertion is speculative, it is not

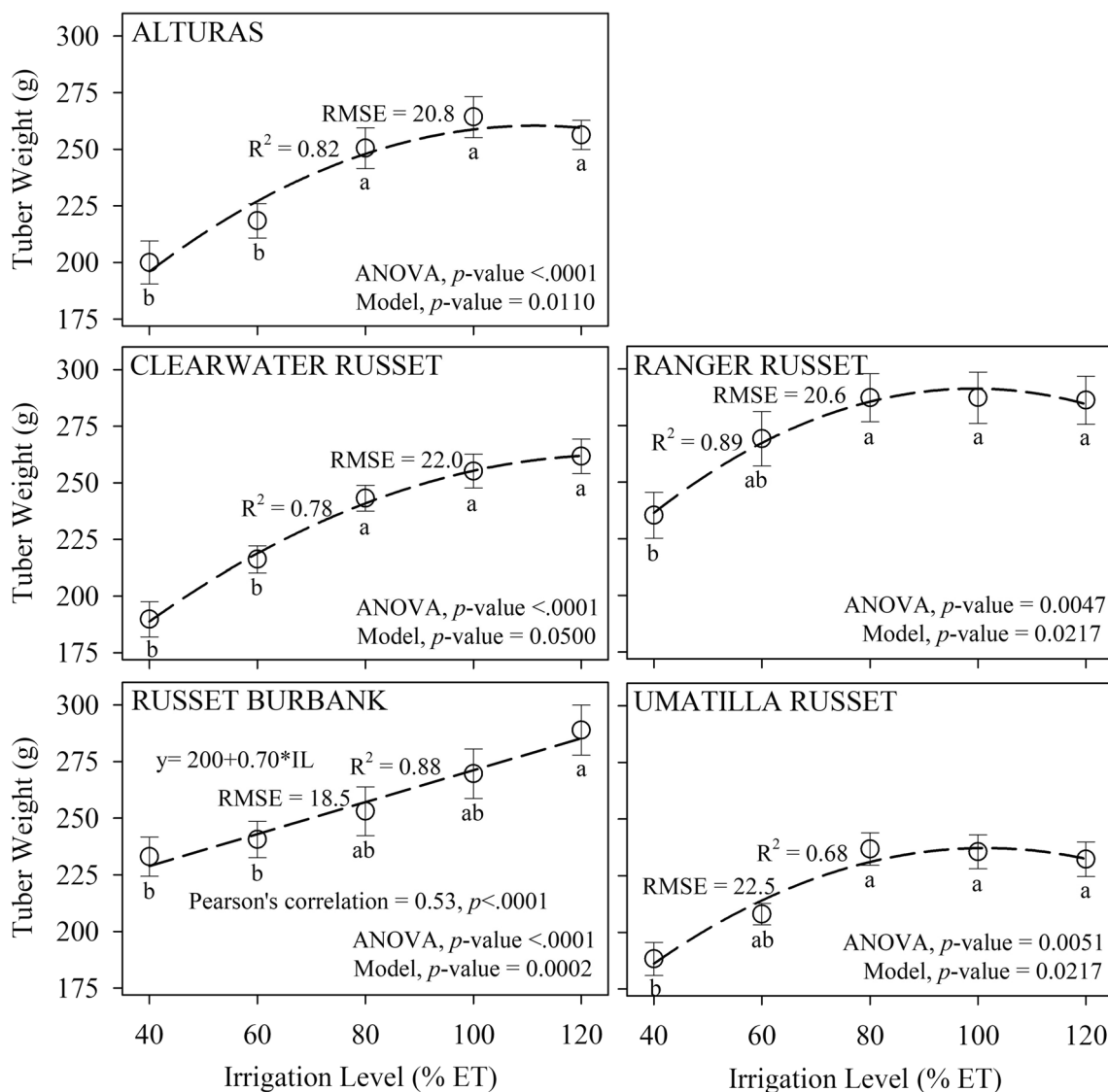


Fig. 8 Analysis of variance, post-hoc comparison, and best fit curve analysis of the mean tuber weight as influenced by five irrigation levels for five potato cultivars, averaged across three years (2018–20).

The error bars are standard error. For each irrigation level, tuber weight with different letters is significantly different. The analysis of variance was conducted with a significance level of 0.05

without merit. Iritani and Weller's (1978) work revealed that tubers harvested one day after vine killing had significantly higher reducing sugars than tubers harvested two weeks after vine killing. Furthermore, Iritani (1981), Ap Rees, and Morrell (1990) substantiated that physiologically mature tubers contain less reducing sugars than immature tubers.

It is noteworthy that in the case of Russet Burbank and Umatilla Russet, the SWC at the most reduced irrigation level, 60% ET, remained notably distant from the 65% readily available water during the last eight weeks of the season. This may imply that potato crops may not need to be stressed to trigger a maturation response late in the season, leading to higher dry matter content.

Tuber Size Distribution Response to Reduced Late-Season Irrigation

A significant difference was found in the means of tubers weighing < 113 g among the five ILs on potato cultivars: Alturas ($p < 0.0001$), Clearwater Russet ($p < 0.0001$), and Ranger Russet ($p = 0.0367$). In the case of the tubers weighing 113 g to 340 g, a significant difference was found among the five ILs' means on potato cultivars: Alturas ($p < 0.0001$), Clearwater Russet ($p = 0.0002$), Ranger Russet ($p = 0.0067$), Russet Burbank ($p = 0.0319$), and Umatilla Russet ($p = 0.0005$). Lastly, on tubers weighing > 340 g, a significant difference was found among the five ILs' means on potato cultivars: Alturas ($p = 0.0002$), Clearwater Russet ($p < 0.0001$), Ranger Russet ($p = 0.00123$),

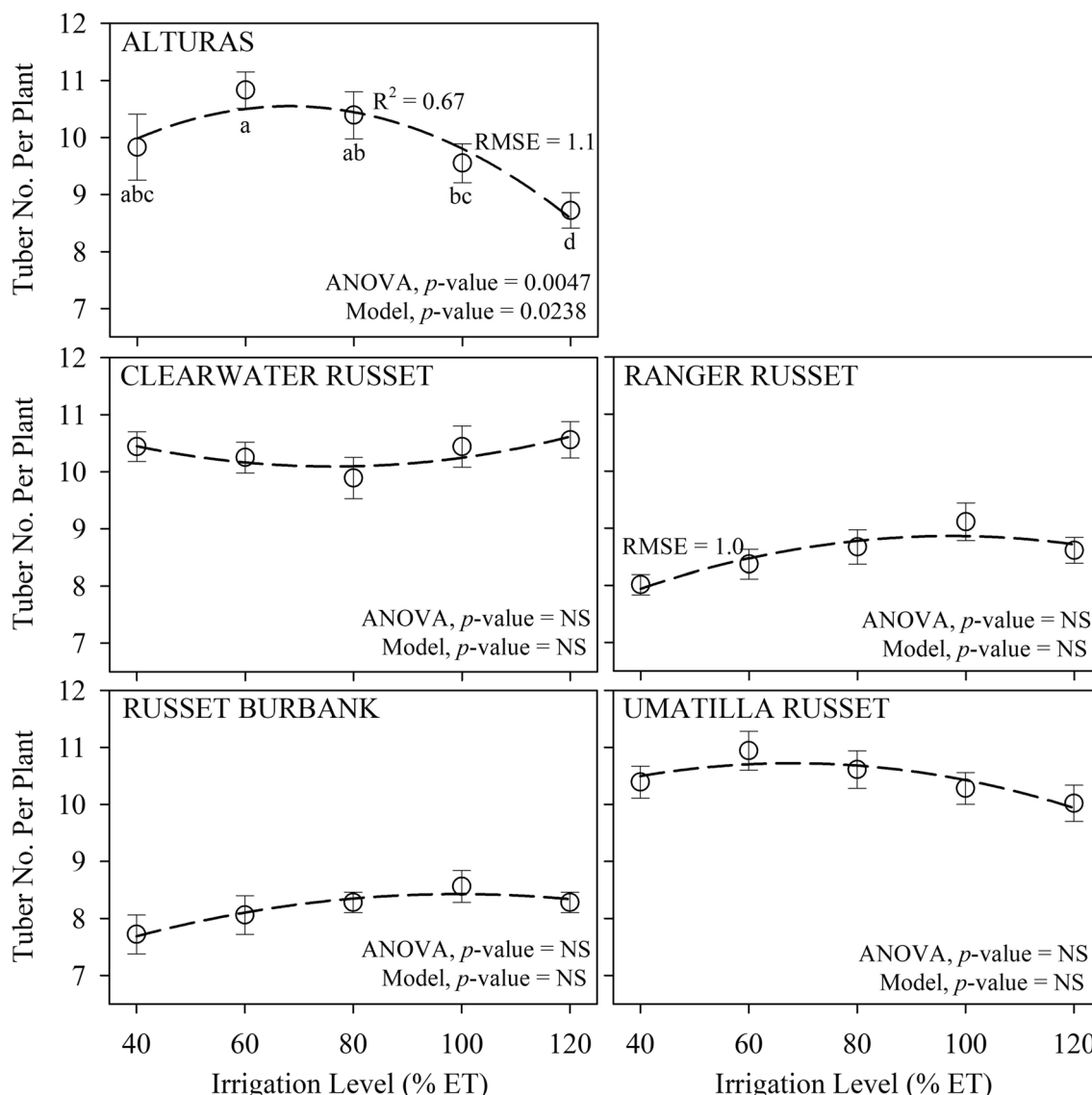


Fig. 9 Analysis of variance, post-hoc comparison, and best fit curve analysis of the mean tuber number per plant as influenced by five irrigation levels for five potato cultivars, averaged across three years (2018–20). The error bars are standard error. For each irrigation level,

the mean tuber weight with different letters is significantly different. The analysis of variance was conducted with a significance level of 0.05

Russet Burbank ($p=0.0261$), and Umatilla Russet ($p=0.0039$). The percentage of tubers that are most desirable for frozen-processing, weighing 113 g to 340 g, was maximized when late-season irrigation was reduced by 40% to 60% across the five potato cultivars. Tubers within this size profile accounted for 55% to 70% of the market yield. A 40% to 60% irrigation reduction from 100% ET late in the season in Alturas and Clearwater Russet led to a significant 5% increase in undersize tubers, tubers weighing < 113 g. Although Ranger Russet and Russet Burbank produced a high number of tubers weighing 113 g to 340 g, the percentage of oversized tubers weighing > 340 g was significantly higher at the expense of undersized tubers compared to the other three cultivars (Table 2).

Tuber Growth Crack Incidence Response to Reduced Late-Season Irrigation

The tuber growth crack incidence means across the five ILs were found to be significantly different only on potato cultivar Alturas ($p < 0.0001$). Tuber growth cracks were not an issue in three potato cultivars, and Russet Burbank produced a tuber growth incidence of less than 2% across the five ILs. A significant positive linear relationship was found between the tuber growth crack incidence and the five irrigation levels (Pearson’s correlation = 0.97, $p < 0.0001$). Tuber growth crack incidence was found to decrease by 7% for each irrigation level reduced. Additionally, the study revealed that the

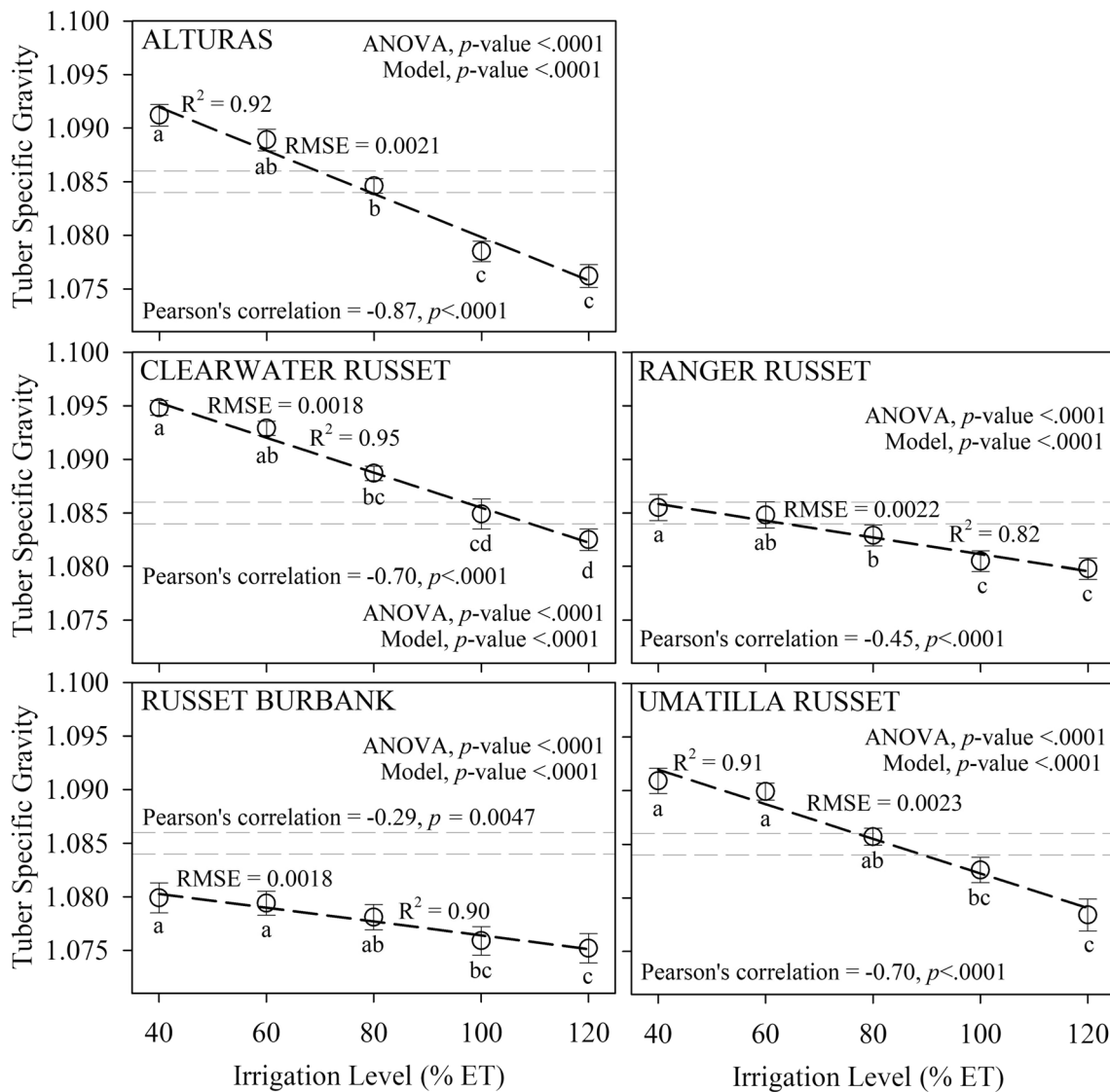


Fig. 10 Analysis of variance, post-hoc comparison, and best fit curve analysis of the mean tuber specific gravity as influenced by five irrigation levels for five potato cultivars, averaged across three years (2018–20). The error bars are standard error. For each irrigation level,

tuber specific gravity with different letters is significantly different. The analysis of variance was conducted with a significance level of 0.05

highest incidence of tuber growth cracks, which amounted to 23.4%, occurred in tubers irrigated with 120% ET. A 60% irrigation reduction from 100% ET late in the season resulted in a corresponding reduction of 21% in the incidence of tuber growth cracks in Alturas (Fig. 11). These findings were in alignment with Robins and Domingo (1956)

Prior scientific investigations have commonly attributed the occurrence of tuber growth cracks to fluctuating environmental conditions, including soil moisture, temperature, and tuber growth vigor (Jefferies and MacKerron 1987; Hiller and Thornton 2008). In the present study, Alturas irrigated with

100% ET late in the season developed a tuber growth crack incidence of 24%, compared to the near 5% observed when irrigated with the 40% ET IL, revealing a 19% reduction in tuber growth crack incidence by reducing irrigation by 60% late in the season (Fig. 11). Since the deficit irrigation levels started after 100 DAP, in disagreement with previous studies (Jefferies and MacKerron 1987; Hiller and Thornton 2008), these findings indicate that most growth cracks in Alturas occurred during the last eight weeks before harvest. Most importantly, these findings indicate that growth cracks can be mitigated with proper soil–water management late in the season.

Table 2 An analysis of variance and post-hoc comparison for tuber size distribution of three tuber size categories. Values averaged across data from three years (2018–20)

Level	Tuber Size Distribution (% Market Yield)				
	Alturas	Clearwater Clearwater	Ranger Russet	Russet Burbank	Umatilla Russet
<i>mean</i>					
Percent of tubers < 113 g					
40% ET	13.5 a	15.1 a	8.1 a	7.4	10.8
60% ET	9.4 b	11.3 a	5.8 ab	6.7	9.0
80% ET	7.0 b	5.9 b	4.6 ab	8.0	7.4
100% ET	7.0 b	5.6 b	4.9 ab	6.1	7.9
120% ET	7.0 b	5.1 b	3.8 b	5.8	7.9
<i>p</i> -value ^a	<.0001	<.0001	0.0367	0.3832	0.0645
Percent of Tubers 113–340 g					
40% ET	60.8 ab	70.3 a	53.7 a	56.5 a	64.3 a
60% ET	63.8 a	66.4 ab	50.1 a	54.5 ab	67.0 a
80% ET	52.7 bc	58.1 bc	45.8 ab	51.8 ab	57.5 ab
100% ET	45.4 c	55.2 c	45.8 ab	46.0 ab	54.1 b
120% ET	48.2 c	50.9 c	38.3 b	42.1 b	51.0 b
<i>p</i> -value	<.0001	0.0002	0.0067	0.0319	0.0005
Percent of Tubers > 340 g					
40% ET	22.7 c	16.4 c	34.5 b	33.3 b	23.4 b
60% ET	26.8 bc	22.2 bc	42.9 ab	37.2 ab	25.1 ab
80% ET	37.6 ab	33.9 ab	48.7 ab	39.7 ab	36.1 a
100% ET	46.8 a	35.3 a	48.4 ab	46.8 a	35.0 a
120% ET	40.6 a	41.7 a	53.6 a	44.0 ab	35.3 a
<i>p</i> -value	0.0002	<.0001	0.0123	0.0261	0.0039

^aBolded *p*-values indicate a significant difference among the irrigation levels with an α level of 0.05

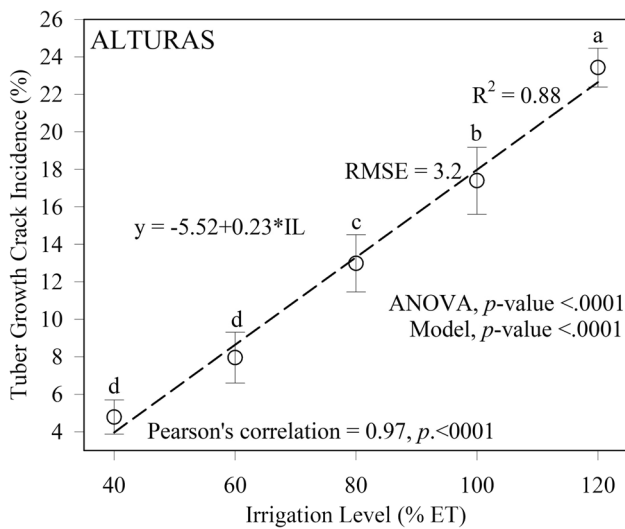


Fig. 11 Analysis of variance, post-hoc comparison, and best fit curve analysis of the mean tuber growth crack incidence as influenced by five irrigation levels, averaged across three years (2018–20). The error bars are standard error. For each irrigation level, tuber growth cracks with different letters are significantly different. The analysis of variance was conducted with a significance level of 0.05

Tuber Blackspot Bruising Incidence Response to Reduced Late-Season Irrigation

The incidence of tuber blackspot bruising (tuber blackspot) was observed in the five potato cultivars. However, the mean incidence of tuber blackspot was only significantly different among the five irrigation levels on Ranger Russet ($p = 0.0006$) and Umatilla Russet ($p < 0.0001$). A reduction in late-season irrigation by at least 60% from 100% ET led to a significant 63% reduction in the incidence of tuber blackspot for Ranger Russet. In the case of Umatilla Russet, a 40% reduction from 100% ET in late-season irrigation resulted in a significant 38% reduction in the incidence of tuber blackspot. For both cultivars, irrigating with an additional 20% more water from 100% ET late in the season did not result in a significant increase in the incidence of tuber blackspot (Fig. 12).

Additionally, a significant linear relationship between the tuber blackspot incidence and the five irrigation levels was found for both Ranger Russet (Pearson’s correlation = 0.87, $p < 0.0001$) and Umatilla Russet (Pearson’s correlation = 0.84, $p < 0.0001$). As late-season irrigation

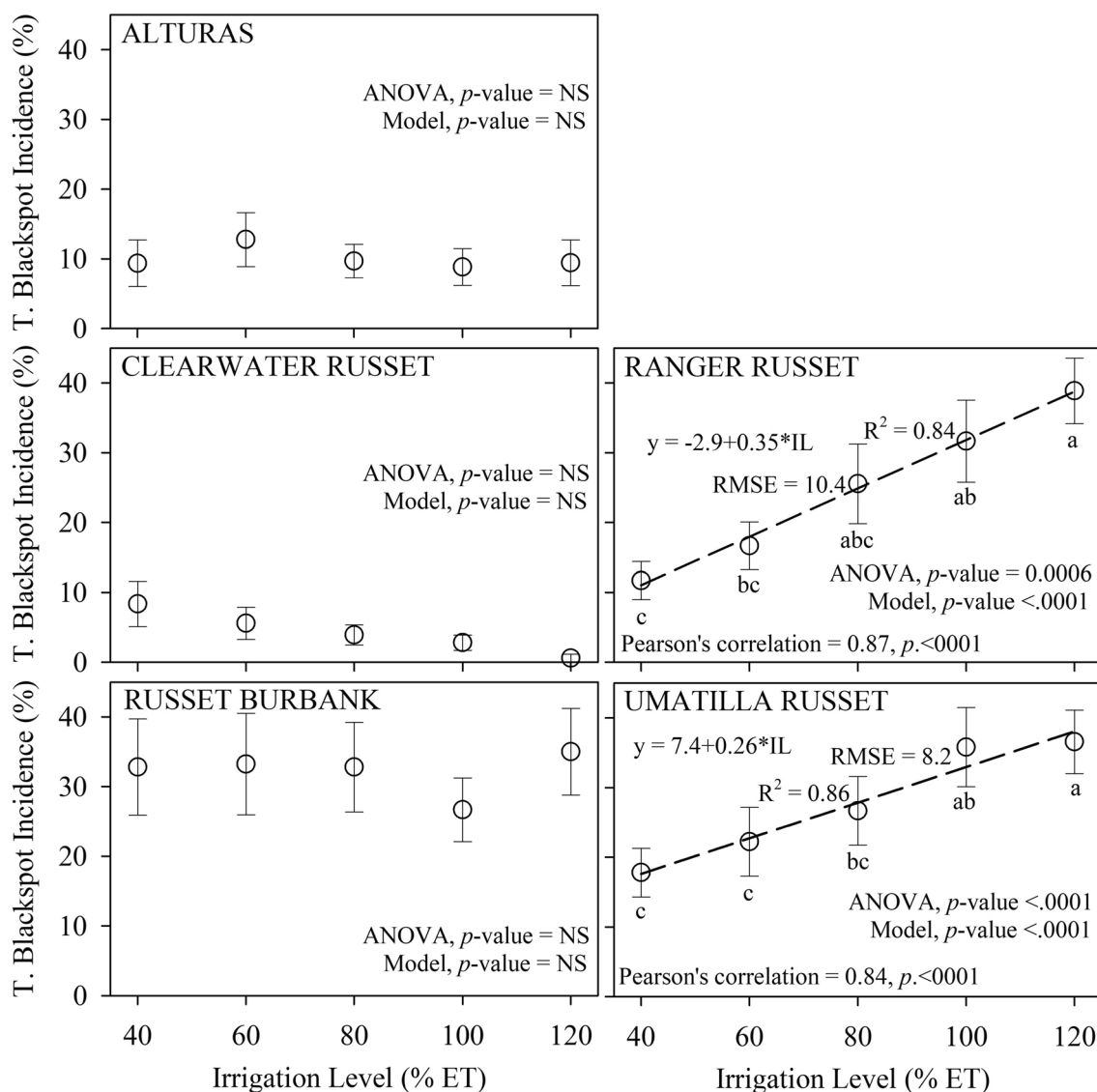


Fig. 12 Analysis of variance, post-hoc comparison, and best fit curve analysis of the mean tuber blackspot incidence as influenced by five irrigation levels for five potato cultivars, averaged across three years

decreased, the tuber blackspot incidence also declined. An associated decrease of 7% and 5% in tuber blackspot incidence followed each incremental decrease in IL for Ranger Russet and Umatilla Russet, respectively (Fig. 12).

The outcomes of tuber blackspot incidence attained in this study stand in contrast to the findings presented by Kunkel and Gardner (1965) and Baumgartner et al. (1982). These prior investigations reported an increase in tuber blackspot incidence as soil moisture decreased and attributed the increase in tuber blackspot incidence to a decrease in tuber turgor pressure. As mentioned above, in Umatilla Russet, SWC conditions were not such that

(2018–20). The error bars are standard error. For each irrigation level, tuber blackspot with different letters is significantly different. The analysis of variance was conducted with a significance level of 0.05

turgor pressure would be reduced even in crops irrigated with 40% ET. The reduction in tuber blackspot incidence with the decreased ILs may have been due to higher physiologically mature tubers due to the lower ILs. In potato tubers, blackspot is attributed to mechanical stress from harvesting and processing, resulting in pulp darkening under the skin. Dark spots in the parenchyma cells result from a catalytic action of polyphenol oxidase, converting phenolic compounds, largely tyrosine, into melanin dyes (Lærke et al. 2002; Grudzinska and Mankowski 2019). A previous study reported relatively lower polyphenol oxidase content in mature tubers (Taranto et al. 2017), substantiating our presumption above.

Beyond the purview of these observations, it is plausible that other latent factors interplay to curtail tuber blackspot incidence amidst the reduction of late-season irrigation. In the context of optimizing grower returns while minimizing the incurrence of bruises, it is recommended to adhere to a late-season irrigation regimen equivalent to 100% ET for Ranger Russet and Umatilla Russet cultivars.

Conclusion

Irrigation scheduling in sensitive vegetable crops like potatoes is challenging. The potato crop must be healthy with a canopy at its peak in growth, and have adequate soil moisture (80% to 100% of soil's field capacity) before reducing irrigation late in the season. However, it is critical that irrigation is scheduled accurately throughout the entire season and adequate soil moisture is maintained in the crop's root zone to ensure that tuber quality criteria are optimized while minimizing tuber quality issues. In the present study, we provided ample evidence that reducing irrigation eight weeks before harvest resulted in higher profit due to improvements in market yield, US No.1 tubers, tuber specific gravity, tuber size distribution, and a reduction in tuber growth cracks. However, three out of the five cultivars were more productive when 100% ET was replaced with irrigation throughout the season. Reduced late-season irrigation as a management tool to optimize yield and quality is more likely to be effective if irrigation scheduling and soil moisture had been managed well earlier in the season. Ultimately, the primary goal of reducing late-season irrigation should be not to stress the crop, but to gently encourage appropriately timed maturation by reducing late-season irrigation.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s12230-024-09948-4>.

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Data availability The data that support the findings of this study are available from the corresponding author, Francisco Gonzalez T., upon reasonable request.

Declarations

Conflict of Interest The authors have no conflict of interest.

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References

- Akkamis, M., and S. Caliskan. 2023. Responses of yield, quality and water use efficiency of potato grown under different drip irrigation and nitrogen levels. *Scientific Reports* 13: 9911. <https://doi.org/10.1038/s41598-023-36934-3>.
- Aliche, E.B., M. Oortwijn, J.M. Theeuwes, C.W. Bachem, R.G. Visser, and C.G. van der Linden. 2018. Drought response in field grown potatoes and the interactions between canopy growth and yield. *Agricultural Water Management* 206: 20–30. <https://doi.org/10.1016/j.agwat.2018.04.013>.
- Allen, R.G., I.A. Walter I.A., R.L. Elliot, T.A. Howell, D. Itenfisu, M.E. Jensen, and R.L. Snyder, eds. 2005. *The ASCE Standardized Reference Evapotranspiration Equation*. Reston, VA: American Society of Civil Engineers.
- Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements*. FAO Irrigation and Drainage Paper 56. Rome: Food Agriculture Organization of the United Nations.
- Ap Rees, T., and S. Morrell. 1990. Carbohydrate Metabolism in Developing Potatoes. *American Potato Journal* 67: 835–847. <https://doi.org/10.1007/BF03044296>.
- Baumgartner, M., E.R. Keller, and F. Schwendemann. 1982. Einfluss von Klimafaktoren auf die blauempfindlichkeit von Kartoffelknollen [Influence of Climatic Factors on the Susceptibility to Black Spot of Potato Tubers]. *Zeitschrift für Acker- und Pflanzenbau*. 151: 185–198.
- Bethke, P.C., A.M.K. Nassar, S. Kubow, Y.N. Leclerc, X.Q. Li, M. Haroon, T. Molen, J. Bamberg, M. Martin, and D.J. Donnelly. 2014. History and Origin of Russet Burbank (Netted Gem) a Sport of Burbank. *American Journal of Potato Research* 91: 594–609. <https://doi.org/10.1007/s12230-014-9397-5>.
- Bohman, B.J., C.J. Rosen, and D.J. Mulla. 2019. Evaluation of Variable Rate Nitrogen and Reduced Irrigation Management for Potato Production. *Agronomy Journal* 111: 2005–2017. <https://doi.org/10.2134/agronj2018.09.0566>.
- Campbell, G.S., and J.M. Norman. 1998. Chapter 2: Temperature. In *Introduction to environmental biophysics*. ed., 15–35. New York: Springer.
- Cappaert, M.R., M.L. Powelson, N.W. Christensen, and F.J. Crowe. 1992. Influence of irrigation on severity of potato early dying and tuber yield. *Phytopathology* 82: 1448–1453.
- Crosby, T.W., and Y. Wang. 2021. Effects of different irrigation management practices on potato (*Solanum tuberosum* L.). *Sustainability* 13. *Multidisciplinary Digital Publishing Institute* 13: 10187. <https://doi.org/10.3390/su131810187>.

- Doorenbos, J., and W.O. Pruitt. 1977. *Crop Water Requirements*. FAO Irrigation and Drainage Paper 24. Rome: FAO of the United Nations.
- Dwelle, R.B., G.E. Kleinkopf, and J.J. Pavek. 1981. Stomatal conductance and gross photosynthesis of potato (*Solanum tuberosum* L.) as influenced by irradiance, temperature, and growth Stage. *Potato Research* 24: 49–59. <https://doi.org/10.1007/BF02362016>.
- Essah, S.C., A.A. Andales, T.A. Bauder, and D.G. Holm. 2020. Response of two colorado russet potato cultivars to reduced irrigation water use. *American Journal of Potato Research* 97: 221–233. <https://doi.org/10.1007/s12230-020-09771-7>.
- Gonzalez, T.F., M.J. Pavek, Z.J. Holden, and R. Garza. 2023. Evaluating potato evapotranspiration and crop coefficients in the Columbia Basin of Washington state. *Agricultural Water Management* 286: 108371. <https://doi.org/10.1016/j.agwat.2023.108371>.
- Grudzinska, M., and D. Mankowski. 2019. Reconditioning and weather conditions affect black spot damage during storage of potato (*Solanum tuberosum* L.) Tubers. *Journal of the science of food and agriculture* 99(11): 4913–4921. <https://doi.org/10.1002/jsfa.9719>.
- Guenel, E., and T. Karadogan. 1998. Effect of irrigation applied at different growth stages and length of irrigation period on quality characters of potato tubers. *Potato Research* 41: 9–19.
- Hang, A.N., and D.E. Miller. 1986. Yield and physiological responses of potatoes to deficit, high frequency sprinkler irrigation. *Agronomy Journal* 78: 436–440. <https://doi.org/10.2134/agronj1986.00021962007800030008x>.
- Hiller, L.K., and R.E. Thornton. 2008. Managing physiological disorders. In *Potato health management*, ed. American Phytopathological Society, 2nd ed., 235–245. Plant Health Management Series. St. Paul: APS Press.
- Ierna, Anita, and G. Mauromicale. 2022. How irrigation water saving strategy can affect tuber growth and nutritional composition of potato. *Scientia Horticulturae* 299: 111034. <https://doi.org/10.1016/j.scienta.2022.111034>.
- Iritani, W.M. 1981. Growth and Preharvest Stress and Processing Quality of Potatoes. *American Potato Journal* 58: 71–80. <https://doi.org/10.1007/BF02855381>.
- Iritani, W.M., and L. Weller. 1978. Influence of Low Fertility and Vine Killing on Sugar Development in Apical and Basal Portions of Russet Burbank Potatoes. *American Potato Journal* 55: 239–246. <https://doi.org/10.1007/BF02852131>.
- Jefferies, R.A., and D.K.L. MacKerron. 1987. Observations on the Incidence of Tuber Growth Cracking in Relation to Weather Patterns. *Potato research* 30. Wageningen: European Association for Potato Research 30: 613–623. <https://doi.org/10.1007/BF02367642>.
- Karafyllidis, D., N. Stavropoulos, and D. Georgakis. 1996. The effect of water stress on the yielding capacity of potato crops and subsequent performance of seed tubers. *Potato Research* 39: 153–163. <https://doi.org/10.1007/BF02358215>.
- Kashyap, P.S., and R.K. Panda. 2001. Evaluation of evapotranspiration estimation methods and development of crop-coefficients for potato crop in a sub-humid region. *Agricultural Water Management* 50: 9–25. [https://doi.org/10.1016/S0378-3774\(01\)00102-0](https://doi.org/10.1016/S0378-3774(01)00102-0).
- Kleinkopf, G.E., D.T. Westermann, M.J. Wille, and G.D. Kleinschmidt. 1987. Specific gravity of russet burbank potatoes. *American potato journal* 64. Washington, DC: Potato Association of America 64: 579–587. <https://doi.org/10.1007/BF02853760>.
- Kunkel, R., and W.H. Gardner. 1965. Potato Tuber Hydration and its Effect on Blackspot of Russet Burbank Potatoes in the Columbia Basin of Washington. *American Potato Journal* 42: 109–124. <https://doi.org/10.1007/BF02862456>.
- Lærke, P.E., J. Christiansen, and B. Veierskov. 2002. Colour of blackspot bruises in potato tubers during growth and storage compared to their discolouration potential. *Postharvest biology and technology* 26. AMSTERDAM: Elsevier BV 26: 99–111. [https://doi.org/10.1016/S0925-5214\(02\)00008-X](https://doi.org/10.1016/S0925-5214(02)00008-X).
- Lane, D. 2010. *Tukey's Honestly Significant Difference (HSD)* 3: 1565–1570.
- Lang, N.S., R.G. Stevens, W.L. Thornton, W. L. Pan, and S. Victory. 1999. Nutrient management guide: Central washington irrigated potatoes. EB 1982: Washington State University Cooperative Extension.
- Larson, P.R., and C.F. Lohrengel. 2011. A New Tool for Climatic Analysis Using the Koppen Climate Classification. *Journal of Geometry* 110: 120–130. <https://doi.org/10.1080/00221341.2011.537672>.
- Leib, B.G., M. Hattendorf, T. Elliott, and G. Matthews. 2002. Adoption and adaptation of scientific irrigation scheduling: trends from washington, USA as of 1998. *Agricultural Water Management* 55: 105–120. [https://doi.org/10.1016/S0378-3774\(01\)00191-3](https://doi.org/10.1016/S0378-3774(01)00191-3).
- Mosley, A.R., S.R. James, D.C. Hane, K.A. Rykbost, C.C. Shock, B.A. Charlton, J.J. Pavek, S.L. Love, D.L. Corsini, and R.E. Thornton. 2000. Umatilla russet: a full season long russet for processing and fresh market use. *American Journal of Potato Research* 77: 83–87. <https://doi.org/10.1007/bf02853734>.
- Novy, R.G., D.L. Corsini, S.L. Love, J.J. Pavek, A.R. Mosley, S.R. James, D.C. Hane, et al. 2003. Alturas: a multi-purpose, russet potato cultivar with high yield and tuber specific gravity. *American Journal of Potato Research* 80: 295–301. <https://doi.org/10.1007/BF02854312>.
- Novy, R.G., J. Whitworth, J. Stark, S. Love, D. Corsini, J. Pavek, M. Vales, et al. 2010. Clearwater russet: a dual-purpose potato cultivar with cold sweetening resistance, high protein content, and low incidence of external defects and sugar ends. *American Journal of Potato Research* 87: 458–471. <https://doi.org/10.1007/s12230-010-9148-1>.
- Onder, S., M.E. Caliskan, D. Onder, and S. Caliskan. 2005. Different irrigation methods and water stress effects on potato yield and yield components. *Agricultural Water Management* 73: 73–86. <https://doi.org/10.1016/j.agwat.2004.09.023>.
- Parent, A.C., and F. Anctil. 2012. Quantifying evapotranspiration of a rainfed potato crop in south-eastern canada using eddy covariance techniques. *Agricultural Water Management* 113: 45–56. <https://doi.org/10.1016/j.agwat.2012.06.014>.
- Pavek, J.J., D.L. Corsini, S.L. Love, D.C. Hane, D.G. Holm, W.M. Iritani, S.R. James, et al. 1992. Ranger russet: a long russet potato variety for processing and fresh market with improved quality, disease resistance, and yield. *American Journal of Potato Research* 69: 483–488. <https://doi.org/10.1007/BF02853837>.
- Pavek, M.J., Z.J. Holden, R.R. Spear, and B.J. Weddell. 2018. Improving land use efficiency and grower revenue by reducing potato row width. *American Journal of Potato Research* 95: 451–462. <https://doi.org/10.1007/s12230-018-9645-1>.
- Pavlista, A.D. 2015. Scheduling reduced irrigation on 'atlantic' potato for minimal effect. *American Journal of Potato Research* 92: 673–683. <https://doi.org/10.1007/s12230-015-9483-3>.
- Rawls, W.J. 1998. Use of soil texture, bulk density, and slope of the water retention curve to predict saturated hydraulic conductivity. *American Society of Agricultural and Biological Engineers* 41: 983–988. <https://doi.org/10.13031/2013.17270>.
- Robins, J.S., and C.E. Domingo. 1956. Potato yield and tuber shape as affected by severe soil-moisture deficits and plant spacing. *Agronomy Journal* 48: 488–492. <https://doi.org/10.2134/agronj1956.00021962004800110003x>.
- Rodrigues, G.C., and L.S. Pereira. 2009. Assessing economic impacts of deficit irrigation as related to water productivity and water costs. *Biosystems Engineering* 103: 536–551. <https://doi.org/10.1016/j.biosystemseng.2009.05.002>.
- Saxton, K.E., and W.J. Rawls. 2006. Soil Water Characteristic Estimates by Texture and Organic Matter for Hydrologic Solutions.

- Soil Science Society of America Journal* 70: 1569–1578. <https://doi.org/10.2136/sssaj2005.0117>.
- Schneider, C.A., W.S. Rasband, and K.W. Eliceiri. 2012. NIH image to imagej: 25 years of image analysis. *Nature Methods* 9: 671–675. <https://doi.org/10.1038/nmeth.2089>.
- Shock, C.C., J.C. Zalewski, T.D. Stieber, and D.S. Burnett. 1992. Impact of early-season water deficits on Russet Burbank plant development, tuber yield and quality. *American Potato Journal* 69: 793–803. <https://doi.org/10.1007/BF02854186>.
- Shock, C.C., E.B.G. Feibert, and L.D. Saunders. 1998. Potato Yield and Quality Response to Deficit Irrigation. *HortScience* 33: 655–659. <https://doi.org/10.21273/HORTSCI.33.4.655>.
- Stalham, M. 2015. *Over-watering potatoes and the risk of growth cracks*. Wales, UK: Agriculture and Horticulture Development Board.
- Stark, J.C., S.L. Love, B.A. King, J.M. Marshall, W.H. Bohl, and T. Salaiz. 2013. Potato Cultivar Response to Seasonal Drought Patterns. *American Journal of Potato Research* 90: 207–216. <https://doi.org/10.1007/s12230-012-9285-9>.
- Storey, R.M.J., and H.V. Davies. 1992. Tuber Quality. In *The Potato Crop: The scientific basis for improvement*, ed. P. M. Harris, 2nd ed., 507–568. World Crop Series. London: Chapman and Hall.
- Taranto, F., A. Pasqualone, G. Mangini, P. Tripodi, M.M. Miazzi, S. Pavan, and C. Montemurro. 2017. Polyphenol Oxidases in Crops: Biochemical, Physiological and Genetic Aspects. *International Journal of Molecular Sciences* 18: 377. <https://doi.org/10.3390/ijms18020377>.
- U.S. Environmental Protection Agency. 2022. *Water Conservation at EPA*. Washington D.C.
- Ullah, H. R., Santiago-Arenas, Z., Ferdous, A., Attia, and A. Datta. 2019. Chapter Two - Improving water use efficiency, nitrogen use efficiency, and radiation use efficiency in field crops under drought stress: A Review. In *Advances in Agronomy*, ed. D. L. Sparks, 156: 109–157. Cambridge, MA: Academic Press.
- USDA-AMS. 1999. *United States Standards for Grades of Potatoes*. Washington, D.C.: US Department of Agriculture.
- USDA-NASS. 2022. *2022 Potato Summary*. USDA-NASS.
- Worthington, C.M., and C.M. Hutchinson. 2005. Accumulated growing degree days as a model to determine key developmental stages and evaluate yield and quality of potato in northeast florida. *Proc. Fla. State Hort. Soc.* 118: 98–101.
- Wright, J.L. 1981. Crop coefficients for estimates of daily crop evapotranspiration. In: *Irrigation Scheduling for Water and Energy Conservation in the 80's*. Proc. Conf. ASAE Publ. No. 23-81. ASAEA, St. Joseph, MI. 18-26.
- Xiong, Y., C.P. West, C.P. Brown, and P.E. Green. 2019. Digital image analysis of old world bluestem cover to estimate canopy development. *Agronomy journal* 111(3): 1247–1253. <https://doi.org/10.2134/agronj2018.08.0502>.
- Yuan, B.Z., S. Nishiyama, and Y. Kang. 2003. Effects of Different Irrigation Regimes on the Growth and Yield of Drip-Irrigated Potato. *Agricultural Water Management* 63: 153–167. [https://doi.org/10.1016/S0378-3774\(03\)00174-4](https://doi.org/10.1016/S0378-3774(03)00174-4).