



Impact of Simulated Wildfire Smoke on Potato Growth, Storage and Profitability

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Abstract

Potato growers and processors throughout the Pacific Northwest have observed that extensive periods of smoke exposure from summer wildfires can have negative effects on potato crops (*Solanum tuberosum* L). Replicated field studies were conducted during 2022 and 2023 to document the impact of smoke exposure on yield, grade and storability of three russet potato cultivars ('Russet Burbank', 'Clearwater Russet', 'Alturas'). Potato plants were treated from July 10 to August 18 each year in clear plastic-covered hoop house enclosures between 6:00 and 9:00am MST, before rising temperatures within the enclosures would cause heat stress. The fuel used to generate smoke consisted of a mixture of hard and soft wood tree species. Tubers were harvested in mid-September, graded, and samples placed into storage at 9°C for 6 months. Yield, quality and decay after storage were used to calculate revenue and smoke impact using a potato processing contract. Potato plants exposed to smoke did not exhibit any visual symptoms and did not senesce earlier than plants not exposed to smoke. Smoke exposure caused a decline in proportion of U.S. No 1 tubers ($p=0.09$), and a slight increase in the proportion of cull tubers ($p=0.08$). The effect of smoke on cull production was more apparent during the 2022 trial when daytime high temperatures were often above the level considered optimum for potato growth, and less apparent in the more moderate conditions experienced during 2023. A similar effect was seen on specific gravity, with smoke treatment causing a significant decline in 2022 but not in 2023. Smoke treatments had no impact on weight loss but decreased decay after six months of storage. The three cultivars tended to exhibit different responses to smoke exposure in terms of proportion of <113 g and >170 g tubers ($p=0.06$ and 0.04 , respectively). Alturas and Russet Burbank exhibited no change in the percentage of <113 g and >170 g tubers due to smoke treatment in both 2022 and 2023. In contrast, Clearwater Russet showed an increase in <113 g tubers in 2022 due to smoke treatment and a decline in 2023. Clearwater Russet also exhibited a significant decline in the proportion of yield that was >170 g in response to smoke treatment in 2022, but no effect in 2023. The impact of smoke on crop revenue was variable, ranging from a 20% decrease to a 17% increase. It is unclear whether cultivar selection could be used as a tool to reduce the risk of losses due to wildfire smoke exposure

Resumen

Los productores y procesadores de papa en todo el noroeste del Pacífico han observado que los períodos prolongados de exposición al humo de los incendios forestales de verano pueden tener efectos negativos en los cultivos de papa (*Solanum tuberosum* L). Durante 2022 y 2023 se realizaron estudios de campo replicados para documentar el impacto de la exposición al humo en el rendimiento, la calidad y la capacidad de almacenamiento de tres variedades de papa tipo russet

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('Russet Burbank', 'Clearwater Russet', 'Alturas'). Las plantas de papa se trataron del 10 de julio al 18 de agosto de cada año en invernaderos de plástico transparente entre las 6:00 y las 9:00 a.m. MST, antes de que el aumento de las temperaturas dentro de las instalaciones causara estrés por calor. El combustible utilizado para generar humo consistía en una mezcla de especies de árboles de madera dura y blanda. Los tubérculos se cosecharon a mediados de septiembre, se clasificaron y las muestras se almacenaron a 9°C durante 6 meses. El rendimiento, la calidad y la descomposición después del almacenamiento se utilizaron para calcular los ingresos y el impacto del humo utilizando un contrato de procesamiento de papa. Las plantas de papa expuestas al humo no mostraron ningún síntoma visual y no presentaron senescencia antes que las plantas no expuestas al humo. La exposición al humo provocó una disminución en la proporción de tubérculos n.º 1 de EE.UU. ($p=0,09$), y un ligero aumento en la proporción de tubérculos de desecho ($p=0,08$). El efecto del humo en la producción de desechos fue más evidente durante el ensayo de 2022, cuando las temperaturas máximas diurnas a menudo estuvieron por encima del nivel considerado óptimo para el crecimiento de la papa, y menos evidente en las condiciones más moderadas experimentadas durante 2023. Se observó un efecto similar en la gravedad específica, ya que el tratamiento del humo provocó una disminución significativa en 2022, pero no en 2023. Los tratamientos con humo no tuvieron ningún impacto en la pérdida de peso, pero disminuyeron la descomposición después de seis meses de almacenamiento. Las tres variedades tendieron a exhibir diferentes respuestas a la exposición al humo en términos de proporción de tubérculos de <113 g y >170 g ($p = 0,06$ y $0,04$, respectivamente). Alturas y Russet Burbank no mostraron cambios en el porcentaje de tubérculos de <113 g y >170 g debido al tratamiento con humo tanto en 2022 como en 2023. En contraste, Clearwater Russet mostró un aumento en tubérculos de <113 g en 2022 debido al tratamiento del humo y una disminución en 2023. Clearwater Russet también mostró una disminución significativa en la proporción de rendimiento de >170 g en respuesta al tratamiento con humo en 2022, pero no tuvo efecto en 2023. El impacto del humo en los ingresos de los cultivos fue variable, oscilando entre una disminución del 20% y un aumento del 17%. No está claro si la selección de variedades podría usarse como una herramienta para reducir el riesgo de pérdidas debido a la exposición al humo de los incendios forestales.

Keywords Stress · Cultivar response · Yield

Introduction

Wildfires in United States (U.S.) have become a national land management issue, and the incidence of major fires is expected to increase as a consequence of changing climate patterns (Jaffe et al. 2020; Liu and Peng 2019). Wildfires burned over 1.5 million ha in the U.S. in 17 of the years between 2001 and 2019 (Jaffe et al. 2020). Particularly harsh fire seasons that severely impacted the western U.S. were seen in 2012, 2015, 2017, 2018, and 2020. The Pacific Northwest (PNW) region has experienced major fires during many of these years, with over 280,000 ha burned in both Idaho and Oregon during 2017 alone (Jaffe et al. 2020). This could have major consequences for the U.S. potato industry as over 60% of total production is concentrated in the PNW (USDA-NASS 2024). Growers in this region have observed earlier plant senescence, reduced yields and a higher incidence of misshapen tubers during years characterized by long periods of intense smoke exposure (A. Waxman, personal communication). The French fry processing industry requires potatoes within a limited range of specific gravity, size and shape to produce high-quality product. Growers of processing potatoes are paid incentives to produce potatoes with these characteristics. Therefore, smoke from wildfires could have a negative economic impact on

the potato industry. However, there have been no previous research studies characterizing the response of potatoes to smoke exposure.

Wildfires discharge substantial amounts of carbon dioxide, black and brown carbon, and other compounds into the atmosphere (Liu and Peng 2019). The resulting particulate matter can be harmful to plants, people, and animals. The chemical complexity and composition of wildfire smoke is very different from industrial pollution. The fires, fueled by rangeland or forest biomaterial, produce smoke of significant variability in both quantity and composition making it challenging to fully understand the impact of these fires on air quality (Jaffe et al. 2020; Liu and Peng 2019). Wildfire smoke contains high concentrations of particulate matter ≤ 2.5 micrometers in diameter ($PM_{2.5}$), carbon dioxide (CO_2), carbon monoxide (CO), and total volatile organic compounds (TVOC) that accumulate in the atmosphere. Ozone (O_3) is a secondary pollutant that has also been reported at elevated levels in smoke plumes (Jaffe et al. 2020). The highest $PM_{2.5}$ concentrations have been detected in western cities, with some daily values exceeding $500 \mu g/m^3$ (Jaffe et al. 2020).

Previous research found that smoke components may have negative or positive impacts on potato growth. For example, Foster et al. (1983) found tuber yield decreased

linearly with increasing concentrations of ozone. Sulfur dioxide (another component associated with air pollution) caused an increase in phytotoxicity symptoms on leaves, but did not affect yield. In contrast, both Steiner et al. (2008) and Kulkarni et al. (2008) reported smoke extracts could have positive impacts on crop growth and yield. Additionally, Gelles et al. (2024) found that exposing potato tubers to smoke as a cold aerosol for 20 h stimulated sprouting in Ranger Russet, Umatilla Russet and Clearwater Russet.

Not all the impacts of smoke exposure can be directly tied to the chemical constituents. For example, heavy smoke concentrations have been reported to reduce light intensity at the canopy level. However, Hemes et al. (2020) reported that smoke creates more diffuse radiation (i.e. light scattering), and plants can use that light more efficiently than direct solar radiation. They concluded that photosynthesis may increase under smoky conditions, but that benefit must be balanced against the injury from pollutants like ozone.

It is likely that potato cultivars could respond differently to smoke exposure. For example, Russet Burbank, the most widely grown cultivar in the U.S., is reported to be susceptible to stress related disorders (Bethke et al. 2014), while newer cultivars such as Clearwater Russet are much less prone to develop sugar ends or other physiological disorders after exposure to stress (Waxman et al. 2018). Foster et al. (1983) reported that both Red Lasoda and Centennial Russet are susceptible to ozone injury, while White Rose was tolerant. It is not known if there is genetic diversity in response to the other chemical constituents of smoke.

Numerous factors, some of which growers can control with farm management decision-making, affect farm profitability. One hypothetical decision for growers is: should I consider the risk of smoke damage when deciding whether to plant Russet Burbank, Alturas or Clearwater Russet?

We initiated these field studies with the objective of documenting the impact of smoke exposure on the growth, development and economic returns of three russet potato cultivars (Russet Burbank, Alturas and Clearwater Russet). We also evaluated potatoes out of storage to determine if smoke exposure impacts weight loss and the incidence of decay. We hypothesized that the three cultivars might react differently to smoke exposure based on their response to

other types of abiotic stresses. Russet Burbank is the most widely grown cultivar in the U.S. with medium-late maturity, medium-high yields, and susceptibility to many abiotic stresses (Bethke et al. 2014). Alturas and Clearwater Russet are late maturing, with higher yield potential and more stress tolerance than Russet Burbank (Novy et al. 2003, 2010).

Materials and Methods

The experiment was conducted during 2022 and 2023 at Parma, ID. The soil type in both.

years was a Greenleaf silt loam previously cropped with wheat, pH 7.5 to 8.3 with approximately 1% organic matter. All fertilizer applications were made according to University of Idaho guidelines (Stark et al. 2004). Each year, hand-cut certified seed of three commonly grown processing potato varieties (Russet Burbank, Alturas and Clearwater Russet) was planted in mid-April at 25 cm in-row seed piece spacing (Table 1).

The field was initially irrigated with a sprinkler system to incorporate herbicides and later changed to drip irrigation to accommodate the need to be in the field each day to apply the smoke treatments. Irrigations were scheduled to maintain available soil water in the root zone above 65–70% throughout the growing season (King et al. 2020).

Individual plots of Alturas and Clearwater Russet were each paired with Russet Burbank to create 2-row plots measuring 1.8 m wide by 10.7 m long. The experiment was arranged in a randomized complete block design with four replications. The potato plants were treated each morning from Monday to Friday during mid-July to mid-August in clear plastic-covered hoop house enclosures (Table 1). The enclosures were made from clear 0.15 mm thick plastic laid over metal hoops (Fig. 1). In 2023, 87% grey knitted shade cloth (Shade Cloth Store, Mundelein, IL) was added to the eastern side of the enclosures to reduce incident sunlight during the exposure period.

Smoke treatments began each day at 6:00am and ended at 9:00am (Mountain Time Zone), before rising temperatures within the enclosures could cause heat stress. The plastic was rolled over the top of the metal frame to form enclosures that allowed smoke to develop at a consistent concentration around the plants. Smoke was generated using two Smoke Daddy Magnum P.I.G cold smokers (Smoke Daddy, Inc., Grunee, IL). The cold smokers were plumbed to a 114 L barrel that was connected to a $0.02\text{ m}^3\text{ s}^{-1}$ forced air blower. Charcoal briquets were first ignited, then the wood added to generate smoke during the entire 3 h exposure period. The fuel blend was an attempt to mimic the hard and soft wood tree species common to wildfires in the western U.S. In 2022, the composition of the fuel blend was 5%

Table 1 Dates of planting, smoke treatment, vine kill, harvest and storage evaluations for three potato varieties grown at Parma, ID during 2022 and 2023

Date	2022	2023
Planting	April 21	April 25
Start of smoke treatment	July 11	July 10
End of smoke treatment	August 19	August 18
Vine kill	September 9	September 17
Harvest	September 22	September 23
Storage evaluations	March 21, 2023	February 28, 2024



Fig. 1 Enclosures made from clear plastic, PVC pipe and metal hoops used to cover both smoke and non-exposed plots. The plastic and shade cloth along the right side was rolled over each enclosure before the start of the daily exposure period (6 am) and then removed when the exposure period ended (9 am)

charcoal, 34% wood chunks (blend of several hard wood species), 15% hickory chips, 10% pine clippings and 36% wood pellets in 2022 (dry wt basis). In 2023, we modified the system to introduce smoke into the air stream after the pump through a venturi system to reduce the accumulation of creosote. This allowed us to alter the composition of the fuel blend to increase the proportion of pine clippings to 23% and hickory chips to 21% while the proportion of wood chunks and wood pellets was reduced to 24% and 23%, respectively. The higher proportion of pine in the fuel blend more closely mimics the typical tree species consumed in wildfires in the western U.S.

Smoke was piped into each smoke-treated enclosure through a 12 mm diameter plastic line that had 3 emitters per enclosure. Smoke concentration was monitored for levels of $PM_{2.5}$, TVOC and CO_2 , using a handheld BR-Smart 128s air quality monitor (BLATN, Beijing, China). Temperature and humidity were monitored using HOBO sensors (Onset, Bourne, MA). The non-treated plots were covered by the enclosures for the same duration each day, and the level of background $PM_{2.5}$, TVOC, CO_2 , temperature and humidity were monitored both within the enclosures and under ambient conditions as outlined above.

The concentration of background smoke in southwest ID was monitored daily via the EPA AirData website (Environmental 2023). Additionally, the daily high temperatures at Parma were monitored during the treatment period each season via the Agrimet weather system website (Bureau of Reclamation 2023). This system has a weather station located in Parma that was less than 1 km away from the experimental site.

Plant senescence was rated each year at the end of the treatment period by visually estimating the proportion of dead leaves and stems in each plot. The plots were vine-killed by removing the plants with a flail in early September and all tubers in the middle 7.6 m of each row were harvested in late September (Table 1). Samples were stored at 13°C, then graded according to USDA specifications for size and external defects (USDA-AMS 1997). The size categories within the U.S. No. 1 and No. 2 grades included < 113 g, 113 g to 170 g, 171 g to 283 g, 284 g to 396 g and > 296 g. Tubers above 113 g that did not meet the grade specifications due to malformation or other defects were classified as culls. For processing contracts, the < 113 g and > 170 g categories, along with the percentage of U.S. No. 1's, U.S. No. 2's and culls were calculated for each plot.

A sample of 20 tubers from the 171 g to 283 g size class was used to determine specific gravity by the weight in air/weight in water method (Kleinkopf et al. 1987). The remaining U.S. No.1 and No. 2 grade tubers from each plot were bulked into samples of approximately 20 kg each and placed back into storage. The temperature in the storage was ramped down by 2°C per week, to a holding temperature of 9°C with 90% relative humidity. The sample was weighed before being taken to the facility at the Kimberly Research and Extension Center, ID for long-term storage at 9°C. These tubers were treated with CIPC (Sprout Nip, Aceto Life Sciences LLC., Port Washington, NY) at a rate of 45.9 ml min⁻¹ for 10 min in mid-November to inhibit sprouting. Samples were removed from storage between late February and mid-March (> 150 days after harvest), reweighed to determine weight loss during storage, and sorted to remove decayed tubers (Table 1). The decayed tubers were also weighed separately.

The field and storage research trials provided data for the quantity/price portion of revenue calculations. We used partial budgeting, a tool for evaluating profitability of management decisions (Kay et al. 2020), to analyze economic impacts. Our focus was on the revenue part of the analysis. The data on tuber grade, size and specific gravity was used to estimate potato price impacts. A frozen potato processing contract, which includes quality-based price penalties and incentives, provided a vehicle to quantify smoke-caused price differences among the cultivars (Waxman et al. 2018).

The data were analyzed using PROC GLM (SAS Institute 2013). Prior to analyzing the data, PROC PLOT was used to plot the residuals against the predicted values to test for normality. Using this method for the variables analyzed, it appeared that the data was normally distributed. Means were separated by LSD (0.10 level) when the F-test indicated significant treatment effects.

Fig. 2 Daily high temperatures during the smoke exposure period in 2022 and 2023. Data were obtained from the Parma, ID Agrimet weather station located within 1 km from the field site

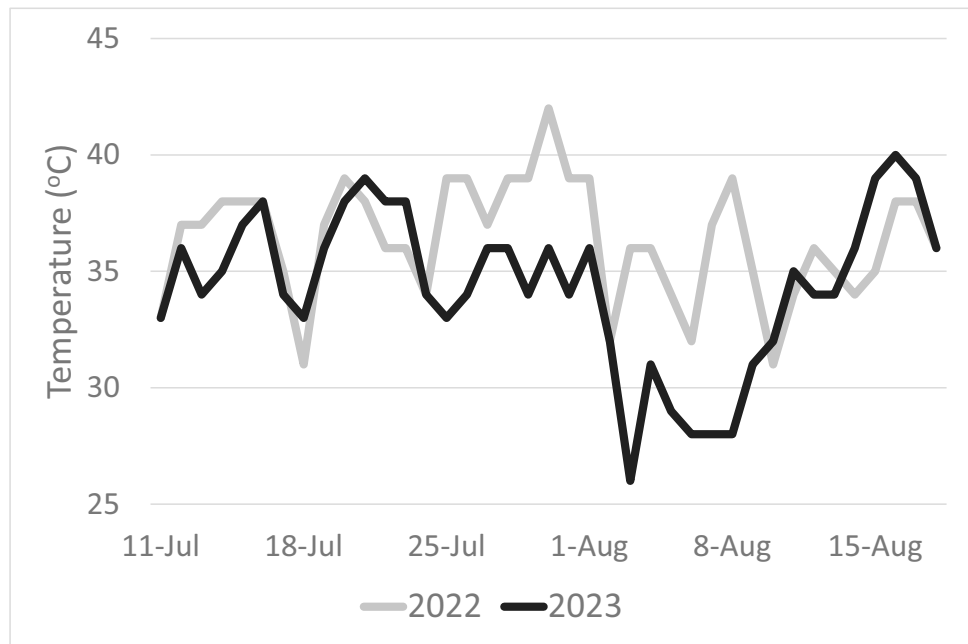


Table 2 Concentration of particulate matter (PM_{2.5}), carbon dioxide (CO₂), and total volatile organic compounds (TVOC) outside (ambient) and inside (non-treated, smoke-treated) of enclosures during the exposure period from mid-July to mid-August in 2022 and 2023. Values are the means of daily readings during the exposure period (6 to 9 am mountain Time) averaged over the 30 days of smoke treatment

Year	PM _{2.5} (μg m ⁻³)	CO ₂ (μL L ⁻¹)	TVOC (mg m ⁻³)
2022			
Ambient	12	453	0.2
Non-treated	12	459	0.4
Smoke-treated	559	516	6.6
2023			
Ambient	13	454	0.2
Non-treated	11	459	0.4
Smoke-treated	551	520	6.6

Results

Conditions Outside the Enclosures

The Treasure Valley region experienced low levels of background smoke during the 2022 and 2023 growing seasons. The air quality index (AQI) reached the moderate category (defined as 9 to 35 μg m⁻³ PM_{2.5}) on 26 of the days during the six-week exposure period in both years (data not shown). These levels of smoke were substantially below those experienced in the enclosure that received the smoke treatment (see below).

Both 2022 and 2023 were unusually hot during the period from mid-July to mid-August when the treatments were conducted, experiencing 27 and 17 days over 35°C, respectively. Conditions during 2022 were consistently hotter than

those experienced during 2023 (Fig. 2), but in both years the plants were exposed to heat stress.

Conditions Inside the Enclosures

PM_{2.5} readings were above 500 μg m⁻³ in the smoke-treatment during the exposure period in both years of the study (Table 2). In contrast, PM_{2.5} levels averaged 12 μg m⁻³ under both ambient conditions and in the non-treated enclosures. Similarly, both CO₂ and TVOC levels were elevated in the smoke-treated enclosures compared to ambient conditions and the non-treated enclosures (Table 2). CO₂ levels averaged about 60 μL L⁻¹ higher for the smoke treatment compared to ambient conditions and inside the non-treated enclosures. TVOC concentrations were about 20 to 30 times higher in the smoke-treated enclosures compared to ambient conditions and inside the non-treated enclosures.

The smoke exposure duration was restricted to 3 h each day to limit changes in environmental conditions within the enclosures. Temperatures within the enclosures started off similar to ambient (un-covered) conditions and then started to increase after sunrise (Fig. 3A). Temperatures tended to stay very close to ambient conditions throughout the remainder of the daily exposure period in 2023, while in 2022 there was an increase of about 5°C by 9 am. Overall, there was less difference in temperature within the enclosures versus outside the enclosures in 2023 compared to 2022, indicating that the shade cloth was effective at limiting the compounding effect of heat stress on the trial results. Relative humidity also tended to be higher within the enclosures than under ambient conditions (Fig. 3B). This was due

Fig. 3 Average hourly temperature (A) and relative humidity (B) within the smoke treated and non-treated enclosures compared to ambient (non-enclosed) conditions within the field. Values are means of data taken from 6 to 9 am averaged over 10-day periods during 2022 and 2023

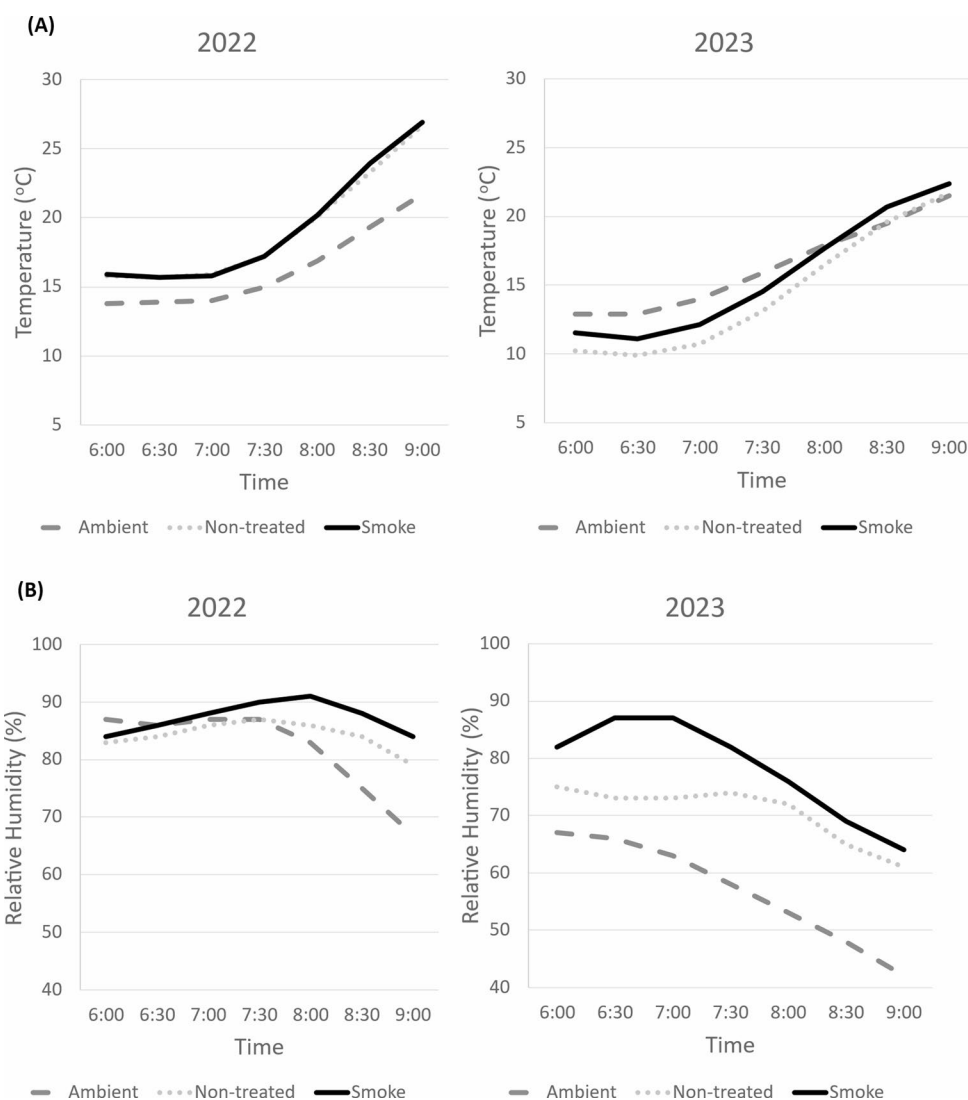


Table 3 Main effect and interaction P values of year, smoke treatment and cultivar on total yield, the proportion of total yield that was <113 g, >170 g, U.S. No. 1, U.S. No. 2, and culls; specific gravity, weight loss and decay after storage for potatoes grown at Parma, ID

Factor	DF	Senescence	Total yield	<113 g	>170 g	US No 1	US No 2	Culls	Specific Gravity	Weight loss	Decay
		<i>P</i> -value									
Year (Y)	1	<0.0001	0.0009	0.0003	<0.0001	<0.0001	0.0342	<0.0001	<0.0001	<0.0001	0.0428
Treatment (T)	1	0.8313	0.2492	0.7994	0.3836	0.0954	0.2347	0.0818	0.4243	0.3486	0.0910
Cultivar (C)	2	<0.0001	0.0032	<0.0001	0.0150	0.0205	<0.0001	<0.0001	<0.0001	0.0337	0.1141
Y x T	1	0.5751	0.5043	0.2794	0.4692	0.1676	0.4345	0.0381	0.0205	0.4650	0.1482
Y x C	2	0.0045	0.0018	0.0005	<0.0001	<0.0001	<0.0001	<0.0001	0.0025	0.1183	0.2444
T x C	2	0.5562	0.7582	0.9865	0.9783	0.9792	0.7901	0.9605	0.6465	0.6213	0.4850
Y x T x C	2	0.6793	0.3396	0.0656	0.0431	0.1594	0.8972	0.6170	0.1107	0.7547	0.4199

to moisture evaporating from the soil being trapped inside the enclosures.

Main Effects and Interactions

The statistical model included year, treatment and cultivar, as well as their interactions. Year and cultivar had significant

effects on almost all measured variables, while smoke treatment only significantly affected the proportion of U.S. No. 1's, culls and decayed tubers (Table 3). There were many significant year x variety interactions, but because the focus of this study was on understanding the impact of smoke on potato productivity and storage they will not be discussed in detail. There were no significant treatment x cultivar

Table 4 Effect of year, smoke treatment and cultivar on senescence of potatoes grown at Parma, ID. Senescence was estimated as the proportion of dead leaves and stems in mid-August of each year. Means followed by different letters are significantly different ($P < 0.10$)

Main Effect	Level	Vine senescence (%)
Year	2022	31 a
	2023	20 b
Treatment	Smoke-treated	25
	Non-treated	26
Cultivar	Alturas	9 c
	Clearwater Russet	19 b
	Russet Burbank	49 a

interactions, indicating that the three varieties in this study reacted to smoke in a similar manner. There were significant year x treatment and year x treatment x cultivar interactions for some variables. The nature of these interactions is presented graphically to aid in interpretation of the results.

Plant Senescence

Russet Burbank exhibited significantly greater vine senescence compared to Alturas and Clearwater Russet, but no differences were found between smoke-treated and non-treated plants (Table 4). This agrees with our observations that there were no visible symptoms of phytotoxicity on plants in the smoke-treated enclosures, despite the relatively high smoke concentrations they were exposed to over the six-week period.

Yield

Both year and cultivar had significant effects on total yield, but yields were not affected by smoke treatment (Table 3). The lack of significant interactions indicated that differences due to year and cultivar were not influenced by smoke levels. Total yields in this trial averaged 73 to 87 Mg ha⁻¹ (Table 5). Yields were over 10 Mg ha⁻¹ higher in 2023 than in 2022. Alturas was consistently the highest yielding cultivar, averaging over 10 Mg ha⁻¹ more than Clearwater Russet and Russet Burbank.

Tuber Size

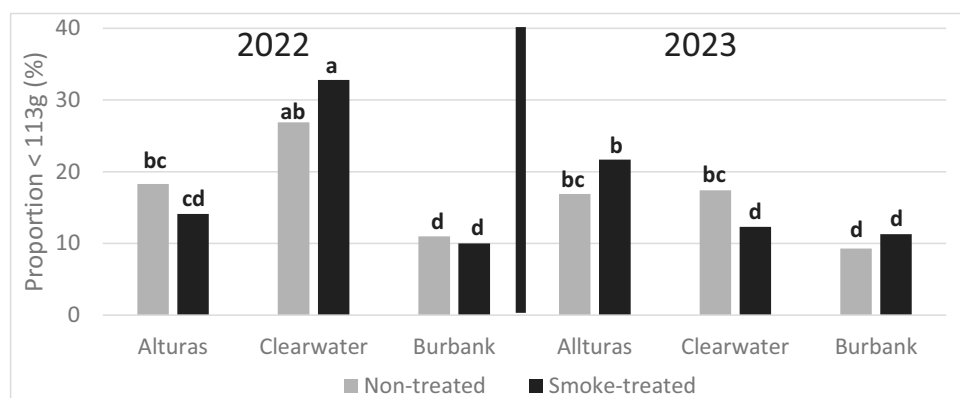
Both year and cultivar had significant effects on the proportion of tubers under 113 g and over 170 g, while the main effect of smoke treatment was not significant (Table 3). The proportion of tubers under 113 g was 7% higher in 2022 compared to 2023, while the proportion over 170 g declined by 19% (Table 5). Clearwater Russet produced more tubers under 113 g and fewer over 170 g compared to both Alturas and Russet Burbank.

There were significant year x treatment x cultivar interactions indicating that the impact of smoke treatment was influenced by both growing season and genetics. For example, Clearwater Russet exhibited an increase in the proportion of tubers under 113 g due to smoke exposure in 2022, but a significant decline in 2023 (Fig. 4). Alturas had an

Table 5 Effect of year, smoke treatment and cultivar on total yield, and percentage of tuber yield under 113 g, over 170 g, U.S. No. 1, U.S. No. 2, culls and specific gravity of potatoes grown at Parma, ID. Means followed by different letters are significantly different ($P < 0.10$)

Main Effect	Level	Total yield (Mg ha ⁻¹)	< 113 g ----- (%) -----	> 170 g ----- (%) -----	US No.1	US No. 2	Culls	Specific Gravity
Year	2022	73.8 b	20 a	45 b	61 b	5 a	15 a	1.065 b
	2023	84.4 a	13 b	64 a	77 a	4 b	4 b	1.074 a
Treatment	Smoke-treated	81.0	17	54	68 b	5	10 a	1.068
	Non-treated	77.5	16	56	71 a	4	9 b	1.069
Cultivar	Alturas	86.7 a	18 b	55 ab	70 a	4 b	8 b	1.070 b
	Clearwater Russet	76.3 b	22 a	50 b	72 a	2 c	5 c	1.074 a
	Russet Burbank	74.3 b	10 c	59 a	66 b	8 a	16 a	1.063 c

Fig. 4 Interaction of year, smoke treatment and cultivar on proportion of tubers under 113 g (by weight) grown at Parma, ID. Different letters are significantly different ($P < 0.10$)



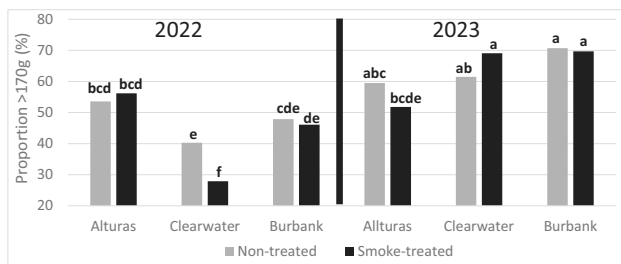


Fig. 5 Interaction of year, smoke treatment and cultivar on proportion of tubers over 170 g (by weight) grown at Parma, ID. Different letters are significantly different ($P < 0.10$)

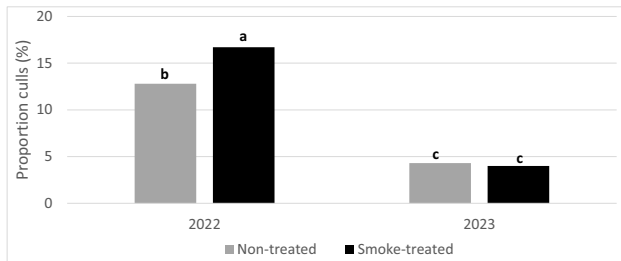


Fig. 6 Interaction of year and smoke exposure on proportion of culls (by weight) of potatoes grown at Parma, ID. Values are means of three potato cultivars. Different letters are significantly different ($P < 0.10$)

opposite response in comparison to Clearwater Russet each year, while Russet Burbank did not exhibit any change in the proportion of small tubers in either year. Likewise, Clearwater Russet exhibited a significant decline in proportion of tubers greater than 170 g due to smoke exposure in 2022, but not in 2023 (Fig. 5). Russet Burbank did not respond to smoke exposure in either year, while Alturas tended to decline in over 170 g tubers in 2023 only.

Grade

The proportion of tubers meeting the U.S. No. 1 grade standard was significantly influenced by year, treatment and cultivar, while U.S. No. 2 grade was only influenced by year and cultivar (Table 3). The proportion of U.S. No. 1 yield was

16% higher in 2023 than in 2022 (Table 5). Smoke treated plants produced 3% less U.S. No. 1 tubers than non-treated plants. Russet Burbank produced 4 to 6% less U.S. No. 1 yield than Alturas and Clearwater Russet, respectively.

Tubers in the U.S. No. 2 grade comprised less than 10% of total yield (Table 5). The proportion of U.S. No. 2's was slightly higher in 2022 compared to 2023. Russet Burbank produced the highest proportion of U.S. No. 2's, followed by Alturas and then Clearwater Russet.

The proportion of cull tubers was significantly influenced by year, treatment and cultivar (Table 3). Culls were a higher proportion of total yield in 2022 than during 2023 (Table 5). The smoke treated plants produced slightly more cull tubers than the non-treated plants. Russet Burbank produced two to three times more cull tubers than Alturas and Clearwater Russet.

There was a significant year $\times$ treatment interaction indicating that the impact of smoke treatment on proportion of culls was influenced by growing season. During 2022, smoke treatment increased the proportion of culls by 4% compared to the non-treated, while in 2023 smoke treatment did not have a significant effect (Fig. 6).

Specific Gravity

Specific gravity was significantly influenced by both year and cultivar (Table 3). Specific gravity averaged 0.009 higher in 2023 compared to 2022 (Table 5). Specific gravity was highest in Clearwater, followed by Alturas and then Russet Burbank.

There was a significant year $\times$ treatment interaction indicating that the impact of smoke treatment on specific gravity was influenced by growing season. During 2022, smoke exposure reduced specific gravity by 0.003 compared to non-treated, while in 2023 smoke had no effect on specific gravity (Fig. 7).

Fig. 7 Interaction of year and smoke exposure on specific gravity of potatoes grown at Parma, ID. Values are means of three potato cultivars. Different letters are significantly different ($P < 0.10$)

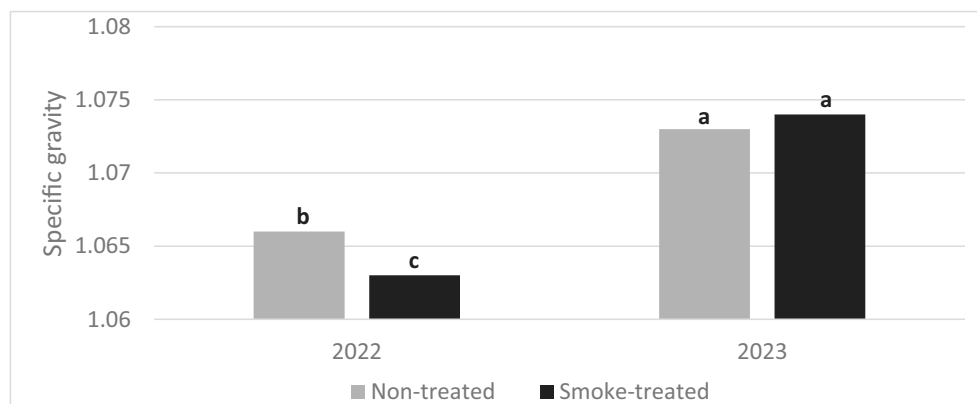


Table 6 Effect of year, smoke treatment and cultivar on weight loss and decay after 6 months storage at 9°C for potatoes grown at Parma, ID. Means followed by different letters are significantly different ($P < 0.10$)

Main Effect	Level	Weight loss (%)	Decay
Year	2022	6.8 a	0.4 a
	2023	0.9 b	0.1 b
Treatment	Smoke-treated	4.0	0.1 b
	Non-treated	3.8	0.4 a
Cultivar	Alturas	3.8 ab	0.4
	Clearwater Russet	4.2 a	0.0
	Russet Burbank	3.6 b	0.3

Table 7 Effect of year, smoke treatment and cultivar on grower revenue for potatoes grown at Parma, ID, using a frozen potato processor contract*

2022	Alturas	Clearwater Russet	Russet Burbank
Revenue - no smoke (\$/ha)	\$10,310	\$9,715	\$9,427
Revenue - smoke (\$/ha)	\$10,546	\$7,803	\$9,958
Smoke impact (\$/ha)	\$236	-\$1,912	\$531
Smoke impact (%)	2%	-20%	6%
2023	Alturas	Clearwater Russet	Russet Burbank
Revenue - no smoke (\$/ha)	\$19,058	\$16,119	\$14,391
Revenue - smoke (\$/ha)	\$19,045	\$18,817	\$15,600
Smoke impact (\$/ha)	-\$12	\$2,697	\$1,209
Smoke impact (%)	0%	17%	8%

*See Tables 3, 4, 5 and 6 for statistical analysis of yield and quality

Weight Loss and Decay in Storage

Year, treatment and cultivar had significant effects on weight loss and decay; but there were no significant interactions (Table 3). Weight loss over the six months of storage was significantly less in 2023 than during 2022 (Table 6). In contrast, a slightly higher level of decay was measured in 2023 compared to 2022. Tubers from plants exposed to smoke exhibited similar weight loss but had lower levels of decay than those from plants not exposed to smoke. Clearwater Russet exhibited higher weight loss than Russet Burbank, while Alturas was intermediate. All three cultivars exhibited very low levels of decay and there were no significant differences between treatments after storage.

Grower Revenue

Revenue increased from 2022 to 2023 for all three cultivars (Table 7). Better growing season weather improved tuber quality and pushed up revenue via quality-based price incentives. For example, Clearwater Russet revenue for smoke plots jumped from \$3,158 to \$7,615 per hectare, an increase of 241%. Other cultivar revenue also increased by smaller percentages. The reasons for increased revenue

were higher yields and higher prices, despite the fact that the same contract was used for both years.

Estimated smoke impacts on revenue ranged from a negative 20% to a positive 17%. Both extremes were from the same cultivar—Clearwater Russet—in different years. These variations were consistent with variations in plot yields and quality.

Discussion

In this study, potato plants were exposed to simulated wild-fire smoke at a concentration of just over $550 \mu\text{g m}^{-3}$ $\text{PM}_{2.5}$ for a six-week period during tuber bulking. This exposure period coincides with the historical data for smoke levels in southwest Idaho that indicates increasing levels of $\text{PM}_{2.5}$ in July, August and September when wildfires most commonly occur (EPA 2023). Jaffe et al. (2020) reported that $\text{PM}_{2.5}$ levels near $500 \mu\text{g m}^{-3}$ have been reported in western U.S. states in the past few years. While potato plants can be exposed to smoke at varying levels for extended periods during extreme fire years, it is unlikely they would experience the levels in this study for an entire six-week period in any growing season. In contrast to conditions in this study, potato plants would typically be exposed to smoke for 24 h periods during the entire duration of wildfire activity. However, we felt that exposing potatoes to high concentrations of smoke for 3 h each day would provide the best method to understand if the chemical constituents of smoke impact potato growth and productivity. Longer daily exposures would have confounded the results by exposing the plants to increased levels of heat stress due to the rise in temperature and humidity within the enclosures. The negative impacts of high temperatures on potato production are already well documented (George et al. 2017; Timlin et al. 2006).

CO_2 levels increased by approximately $60 \mu\text{L L}^{-1}$ within the enclosures during smoke exposure. CO_2 constitutes about 90% by mass of all emissions from wildfires, but it has not been reported to substantially increase the ambient concentrations in large regions during wildfires (Jaffe et al. 2020). In contrast, the concentration of TVOC within the enclosures during smoke exposure increased by 20 to 30 times. This result is in line with reports that TVOC are one of the most common non-carbon constituents of smoke, making up about 15% of the emissions compared to 8% for $\text{PM}_{2.5}$ (Jaffe et al. 2020).

Potato plants exposed to smoke did not exhibit any visual symptoms and did not senesce earlier than plants not exposed to smoke. We also did not observe any differences in plant injury or senescence associated with smoke exposure in the three cultivars evaluated. Foster et al. (2014) previously reported that potato cultivars can differ in sensitivity

to ozone, which can be produced from the components of smoke. This lack of foliar injury would explain why there was not a consistent effect of smoke on total tuber yield (77.5 vs. 81.0 Mg ha⁻¹ for the non-treated and smoke treated, respectively). It is possible that the numerically higher total yield produced by the plants exposed to smoke was associated with the elevated CO₂ levels in the enclosures as increased CO₂ has been reported to improve yields of multiple crop plants, including potatoes (George et al. 2017). However, smoke may also be associated with an increase in the concentration of ozone under certain conditions, which may cause leaf injury and reduce photosynthesis (Foster et al. 1983; Hemes et al. 2020).

Plants exposed to smoke did suffer in the proportion of U.S. No. 1 yield, which was reduced by 3% ($p=0.09$) as compared to plants not exposed to smoke. Smoke exposure also slightly increased the proportion of misshapen tubers graded as culls ($p=0.08$). This effect was more apparent during the 2022 trial when daytime high temperatures were often above the level of 20°C to 25°C considered optimum for potato growth (Timlin et al. 2006), and less apparent in the more moderate conditions experienced during 2023 (Fig. 6). The 5°C increase in temperatures along with the increase in relative humidity within the enclosures measured in 2022 could have increased the level of heat stress during the six-week exposure period. The addition of shade cloth during 2023 reduced the temperature difference between ambient and inside the enclosures which may partly explain why tuber yield and percentage of U.S. No. 1 tubers declined and percentage of culls was higher in 2022 than in 2023. The significant interaction between year and treatment indicated that smoke exposure tended to cause a decline in specific gravity and an increase in culls in the hotter year (2022). It is possible that smoke acts as a general stress to potato plants, and that stress may be more pronounced when the plant is suffering from additional stresses such as heat, water, nutrient or disease (Thornton et al. 2020). Additional research would be needed to determine if the stress caused by smoke exposure is compounded by other environmental or management stresses.

There was a complex interaction between year, smoke treatment and cultivar in terms of proportion of less than 113 g and over 170 g tubers ($p=0.065$ and 0.043 , respectively). Alturas and Clearwater Russet tended to exhibit opposite reactions to smoke in terms of tuber size each year, while Russet Burbank did not react to smoke exposure in either year (Figs. 4 and 5). It is difficult to conclude from these results whether or not breeding could be used as a tool to reduce the risk of losses due to wildfire smoke. Now that we have established a protocol for exposing plants to smoke under field conditions it would be advisable to screen a wider range of cultivars to see if any of them exhibit resistance to stress caused by wildfire smoke.

Exposure to smoky conditions during tuber development did not have any consistent impact on weight loss in storage and tended to decrease the incidence of decay. Even during the 2022 study, when weight loss in storage was relatively high, there was no evidence of smoke exposure increasing losses in storage. These results do not support industry observations that weight loss and decay increase in growing seasons with intense smoke exposure. However, seasons with the most intense wildfires also tend to be unusually hot and growers usually increase water applications under those conditions to match the increase in evaporative demand by the crop. Overapplication of water towards the end of tuber bulking can increase the incidence of several common diseases of stored potatoes (Stevenson et al. 2001), which may explain these observations.

Gelles et al. (2024) reported that exposure of seed tubers to smoke for 20 h during storage increased the rate of sprout development. Tubers in this study were treated with the sprout inhibitor CIPC within 60 days after harvest, and no sprouts were visible when the tubers were removed from storage approximately 90 days later. Therefore, it was not possible to determine if exposure to smoke prior to harvest influences tuber dormancy in this study.

Smoke impacts on grower revenue were consistent with yield, quality and storage findings. Grower prices for contracted frozen-processing potatoes consist of three parts: (1) base price, (2) price adjustments for quality and (3) price adjustments for length of storage. This study found that smoke significantly impacted three measures: U.S. No. 1's, culls and storage decay. Since the three cultivars reacted similarly to smoke, there seems to be little reason to consider smoke risk when deciding which of the three cultivars to plant for frozen potato processing. Other potato pricing mechanisms could lead to a different recommendation. The processor contract used in this study specifies a penalty for each percent U.S. No. 1 below 50%, but no incentive payments above 50%. Pricing mechanisms that reward higher US No.1's could help identify cultivars that are more profitable during high-smoke years. Current fresh potato marketing mechanisms do not put a pricing cap on the percentage of U.S. No. 1 tubers.

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Data Availability Data is available upon request.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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