Am. J. Potato Res. (2016) 93:474–484
DOI 10.1007/s12230-016-9524-6

A Historical Look at Russet Burbank Potato (*Solanum tuberosum* L.) Quality Under Different Storage Regimes

Yi Wang[1] **· Tina L. Brandt**[1] **· Nora L. Olsen**[1]

Published online: 6 June 2016

Abstract Russet Burbank is the predominant potato (*Solanum tuberosum* L.) cultivar grown and stored for fresh market and frozen processing (French fry) use in North America. Multi-year assessments of potato tuber quality under different storage regimes can provide information about a cultivar's ability to retain process quality when challenged with seasonal variations across multiple years. The objective of a 15-year study initiated in 1999 was to evaluate the quality of Russet Burbank tubers grown and stored at the Kimberly Research and Extension Center. Potatoes were measured for specific gravity at harvest and stored for eight months under three temperatures (5.6, 7.2 and 8.9 °C) and periodically sampled throughout the storage season to determine dormancy length, sugar content, fry color and mottling severity (a quality issue), and weight loss. The year in which the crop was grown significantly ($p < 0.001$) affected all quality characteristics except specific gravity (average ranged between 1.071 and 1.081). Tubers held during the 2011–2012 and 2013–2014 storage seasons exhibited generally higher glucose, darker fry color, more severe mottling, and higher weight loss. Average sucrose content at 7.2 °C and 8.9 °C across the 15 years significantly decreased over the eight-month storage while average glucose content remained consistent after first month of storage. Average percent weight loss across the 15 years was 6.1 % after eight months in storage. This 15-year study emphasized that variation of post-harvest storage quality from year to year was likely a result of variable seasonal growing conditions. Storage temperatures between 7.2 and 8.9 °C were the optimum range for storing fry processing Russet Burbank potatoes and the warmer temperature of 8.9 °C appears to ameliorate the seasonal effects on glucose content and fry color to maintain better processing quality throughout storage.

Resumen Russet Burbank es la variedad predominante de papa (*Solanum tuberosum* L.) que se cultiva y se almacena paras mercado fresco y procesamiento congelado (papas a la francesa) en Norteamérica. Evaluaciones multianuales de la calidad del tubérculo de papa bajo diferentes regímenes de almacenamiento pueden proporcionar información acerca de la habilidad de una variedad para retener la calidad de proceso cuando se le enfrenta a variaciones de ciclos de cultivo a lo largo de muchos años. El objetivo de un estudio de 15 años, iniciado en 1999 fue evaluar la calidad de los tubérculos de Russet Burbank cultivados y almacenados en el Centro Kimberly de Investigación y Extensión. A las papas se les cuantificó la gravedad específica a la cosecha y se almacenaron por ocho meses bajo tres temperaturas (5.6, 7.2, y 8.9 °C) y se muestrearon periódicamente a lo largo del período de almacenamiento, para determinar la longitud de la dormancia, contenido de azúcar, color del freído, severidad de moteado (un aspecto de calidad), y pérdida de peso. El año en el que creció el cultivo afectó significativamente ($p < 0.001$) todas las características de calidad excepto la gravedad específica (el promedio fluctuó entre 1.071 y 1.081). Los tubérculos de los períodos de almacenamiento 2011–2012 y 2013–2014, exhibieron generalmente glucosa más alta, color más oscuro de freído, moteado más severo y pérdida de peso más alta. El contenido promedio de sacarosa a 7.2 °C y 8.9 °C a lo largo de los 15 años disminuyó significativamente sobre el almacenamiento de ocho meses, mientras que el contenido promedio de glucosa permaneció consistente después del primer mes de almacenamiento. El promedio de porcentaje de pérdida de peso a lo largo de los 15 años fue 6.1 %

✉ Yi Wang
yiw@uidaho.edu

[1] Kimberly Research and Extension Center, University of Idaho, 3806 North 3600 East, Kimberly, ID 83341, USA

después de ocho meses en almacén. Este estudio de los 15 años enfatizó que la variación de la calidad en el almacenamiento postcosecha de año a año era probablemente el resultado de las variaciones estacionales de las condiciones de crecimiento. Las temperaturas de almacenamiento entre 7.2 °C y 8.9 °C fueron la amplitud óptima para procesamiento de frituras de papas Russet Burbank, y las temperaturas más cálidas de 8.9 °C parecen mejorar los efectos estacionales del contenido de glucosa y color de freído para mantener mejor calidad de proceso a lo largo del almacenamiento.

Keywords Potatoes · Russet Burbank · Seasonal variation · Storage temperature · Storage quality

Abbreviations

LTS Low-temperature sweetening
FW Fresh weight

Introduction

Potato (*Solanum tuberosum* L.) is the leading vegetable crop in the U.S. with per capita consumption of about 51 kg annually, including 35 kg processed potatoes and 16 kg fresh market (Amer et al. 2014). Russet Burbank, a cultivar with an oblong tuber shape and high starch content, continues to dominate the North American French fry and fresh market industry (Coleman et al. 2003) due to excellent storage characteristics (Rommens et al. 2006) as well as good processing and culinary qualities (Love et al. 2003). In 2014, Russet Burbank accounted for 37.2 % of the planted acreage in the major potato production areas (USDA and NASS-Northwest Regional Field 2014).

For both fry processors and fresh market suppliers, a constant year-round supply of potatoes is required, creating the vital importance to have long-term storage (>6 months) to maintain the desired post-harvest quality (Sonnewald and Sonnewald 2014). Therefore, cultivars that exhibit long dormancy and light fry color when storage temperatures are lower than 10 °C are preferred (Kyriacou et al. 2009). Russet Burbank potatoes can be stored for as long as 12 months with the proper application of sprout inhibitors and control of relative humidity, ventilation, and storage temperature in the absence of major diseases (Zaehringer et al. 1966; Bethke 2014).

Sprouting is a major cause of losses in marketable potatoes during storage (Foukaraki et al. 2014), due to respiration and growth and water loss from the sprout tissue (Daniels-Lake et al. 2005). Low relative humidity facilitates evaporative water loss from tubers and increases incidence of pressure bruise (Castleberry and Jayanty 2012; Schippers 1971). Inadequate ventilation contributes to free water formation that promotes pathogen infection and spread (Bethke 2014). Temperature is an important factor for potato storage. Tuber respiration, sprouting, weight loss, chemical composition, relative humidity of the storage environment, and storage disease development can all be influenced by temperature. Higher storage temperatures enhance sprouting activity, tuber dehydration and decay (Kyriacou et al. 2009), and lower temperatures result in low temperature sweetening (LTS) characterized by reducing sugar accumulation (Zommick et al. 2014). During processing, reducing sugars react with free amino acids to generate dark fry color in the non-enzymatic Maillard Reaction (Muttucumaru et al. 2015). Consequently, appropriate storage temperatures must be applied for potatoes destined for different markets. Potatoes intended for French fry processing are typically stored at 8.3 °C to 10.0 °C and for fresh use at 4.4 °C to 10.0 °C (Kleinkopf and Olsen 2003).

A comprehensive evaluation of processing cultivars should encompass detailed reporting on storage profiles (Kyriacou et al. 2009). Information on tuber dormancy length, sugar accumulation, fry color, weight loss, and other storage quality attributes during controlled-temperature storage is critical for the industry because storage managers will use this information to select and store potatoes to best meet the needs of consumers. Since storage regimes vary among regions and managers, cultivars with stable performance across various storage regimes would have a high probability of commercial success (Rak et al. 2013).

Influences of storage temperature, ventilation, humidity, and sprout inhibitor application on storage quality of Russet Burbank cultivar have been well documented (Cunningham et al. 1971; Sparks 1973; Boe et al. 1974; Iritani and Weller 1976; Bogucki and Nelson 1980; Lammerink 1989; Yang et al. 1999) for decades. However, there has not been a study that aims at measuring the response of Russet Burbank potatoes to long-term storage conditions over many years and evaluating quality variations between seasons, storage temperatures, and storage durations. The objective of this study was to evaluate quality of Russet Burbank potatoes grown and stored under three storage temperature regimes during each 8 month post-harvest storage season for fifteen years. In this manuscript, “year” means growing season plus storage season, and is used interchangeable with “season”.

Methods and Materials

Agronomic Practices

Field trials were conducted annually from 1999 to 2014 to evaluate the quality of the cv. Russet Burbank during eight months of post-harvest storage under three temperatures (5.6 °C, 7.2 °C, and 8.9 °C) at the Kimberly Potato Storage Research Facility, Kimberly, Idaho. Potatoes were grown at the Kimberly Research and Extension Center, University of Idaho (latitude: 42.5°N; longitude: 114.4°W; elevation: 1194 m). Planting time in each year ranged from mid- to late- April, and harvest time ranged from mid- to late-September. The soil type was Portnuef Silt Loam. Certified Russet Burbank seed tubers were hand or machine cut to an average seed piece size of 57-71 grams, and planted approximately 16 cm deep, 30 cm in-row and 91 cm between-row spacing. Irrigation, fertility, and pesticide applications were based on the best management practices recommended by the University of Idaho (Stark and Love 2003). Target N, P, and K were 315, 48, and 411 kg ha^{-1}, respectively. Mechanical vine killing was conducted in early September (approximately 14 days before harvest) of each year.

Storage Practices

At harvest, three replications of 4.5 kg of potatoes were randomly selected from the harvested pile, washed and measured for specific gravity using the weight in air – weight in water method (Kleinkopf et al. 1987). Another three replications of 45 kg potato tubers were randomly selected and placed into each of six bins at the Kimberly Potato Storage Research Facility. Each bin was maintained at 12.8 °C for the purpose of wound healing for fourteen days. Temperatures were then decreased at a rate of 0.3 °C per day to final holding temperatures of 5.6, 7.2, and 8.9 °C. Relative humidity was maintained at 95 % ± 3 % for all bins throughout the entire duration of storage. The sprout inhibitor, Isopropyl N-(3-chlorophenyl)carbamate (CIPC, Decco Chemical, at 78.6 % a.i.), was applied to three bins (one at each temperature) as a thermal aerosol at a rate of 22 mg Kg^{-1} approximately 60 days after harvest. Tubers used to evaluate dormancy length were stored in three separate bins not treated with CIPC. All other tubers assessed for storage quality were treated with CIPC. Post-harvest quality measurements, including dormancy length (beginning in 1999), glucose and sucrose content (beginning in 1999), fry color, mottling severity, incidence of sugar end defect (beginning in 2003), and percent fresh weight loss (beginning in 2005), were assessed at 1 month intervals for 8 months starting at harvest.

Sugar Extraction and Analysis

Glucose and sucrose were determined from a 10-tuber sample with three replications from each temperature within one week of harvest and then monthly in storage using the method of Sowokinos et al. (2000) with modifications. Tubers were washed, air dried, and cut into planks (3.0 cm x 0.8 cm x length of tuber) by a Keen Kut Shoe Stringer French fry cutter. Two hundred grams of tuber tissue from the center of the ten planks were bulked and juiced with an Acme Juicerator (Acme Equipment, Spring Hill, FL) in 150 mL of sodium-phosphate buffer (0.05 M, pH 7.2). The final volume of the homogenate was brought up to 275 mL with the same buffer. Glucose and sucrose concentrations were measured using a YSI model 2700 Select Analyzer (Yellow Springs Instrument Inc., Yellow Springs, OH) as per manufacturer's recommendations and expressed on a percent fresh weight basis.

Assessment of Fry Color, Mottling Severity and Sugar End Defect

One fried plank from each of the ten tubers per replication (three replications) used in the sugar extraction and analysis was used for fry color determination. Planks were fried in canola oil at 191 °C for 3.5 minutes and then blotted dry to remove extra oil. Fry color was determined within the first 3 minutes after frying using a model 577 Photovolt Reflection Meter (model 577, Photovolt Instruments Inc., Minneapolis, MN). A green filter was used and calibrated, using a black-cavity standard as 0.0 % reflectance and a white plaque as 99.9 % reflectance. Measurements were taken on the bud and stem ends of each plank and the average of the two ends were calculated and reported. A relationship between the USDA standard fry color and the photovolt reflectance was previously established (Kincaid et al. 1993). A USDA fry color rating 1 was equal to a 44.0 or greater reflectance reading, a USDA 2 rating was less than 44.0 to 35.0 reflectance reading, a USDA 3 rating was less than 35.0 to 26.0 reflectance reading, and a USDA 4 rating was less than 26.0 reflectance reading. Therefore, higher photovolt reflectance readings are associated with lighter fry color. After fry color determination, the presence or absence of sugar end defect was recorded for each plank. A plank was considered to have a sugar end defect if a predominant color of number 3 or darker, when compared with the USDA Munsell Color Chart for French fried potatoes, was seen on any 2 sides extending 13 mm or more from the end of the fried plank.

Mottling severity evaluations were done on the same 10 planks from each replication for fry color determination. Mottling is characterized by thin thread-like areas of dark color throughout the cortex tissue of tubers. The severity rating scale for mottling was 1 = no mottling, 2 = mild mottling (light colored, non-uniform surface browning not covering the entire fried plank), 3 = moderate mottling (light colored, non-uniform surface browning covering the entire fried plank), and 4 = severe mottling (dark colored, non-uniform surface browning covering the entire fried plank).

Measurement of Approximate Dormancy Length

Three replications of 10 tubers in each of the three non-CIPC-applied bins were rated for sprout development every 20–30 days until sprouting occurred. Sprouting was evaluated on a scale of 1 to 4 with 1 = no sprout activity, 2 = sprouting just started (peeping), 3 = sprout length ≤5 mm, 4 = sprout length > 5 mm. Dormancy break is defined as the point at which sprout elongation (sprout rating of 3) is beginning to occur in 80 % of the sampled tubers.

Weight Loss

Weight loss data was collected on 3 replications of 4.5 kg sound, whole, unwashed tubers contained in polypropylene mesh bag at each storage temperature. Tuber sample fresh weights were recorded prior to placing in storage. Sample bags were weighed each month beginning at harvest and ending in early June of the following year. Weight loss was reported on a percent fresh weight basis and averaged across the three storage temperatures and storage duration in each season.

Data Analysis

Data analysis was performed following a three-factor factorial design, with season, storage temperature, and storage duration as the three factors, and variation between the three replications as the error term. For the glucose and sucrose, fry color, mottling severity, specific gravity, and weight loss data, analysis of variance (ANOVA) was conducted using the PROC GLM procedure in SAS (version 9.5). Means were separated using Fisher's LSD at the $\alpha = 0.05$ level.

Results

Glucose and Sucrose

Effects of year, storage temperature, storage duration, and the two-way and three-way interactions on glucose and sucrose content were all significant ($p < 0.001$, Table 1).

With the exception of immediately after harvest, average glucose content over the 15 seasons was consistently higher in tubers stored at 5.6 °C than in those stored at 7.2 °C and 8.9 °C (Fig. 1a, b, c). Average glucose content at all three temperatures showed a similar trend during the eight-month post-harvest storage period: increasing at the beginning of storage, remaining relatively stable thereafter, and decreasing till the end of the storage. The magnitude of change at 5.6 °C was significantly greater than at 7.2 °C and 8.9 °C ($p < 0.05$, Fig. 1a, b, c). The ranges in glucose levels (maximum minus minimum) over the 8-month storage seasons at 5.6, 7.2 and 8.9 °C were 0.185, 0.091 and 0.071 % FW, respectively (Table 2). Average glucose content across the three storage temperatures in the 2011–2012 and 2013–2014 seasons were among the highest compared with most of the other seasons ($p < 0.05$, Table 2). Average glucose content across the 15 seasons at 5.6 °C was significantly higher than at 7.2 and at 8.9 °C ($p < 0.05$, Table 2).

Average sucrose content at 5.6 °C storage temperature significantly ($p < 0.05$) increased from 0 month to 2 month and decreased thereafter (Fig. 1d). At 7.2 °C, sucrose content remained constant from 0 to 3 months and then significantly decreased through 8 months ($p < 0.05$, Fig. 1e). By contrast, the decrease in sucrose concentration was linear over the entire storage period at 8.9 °C ($R^2 = 0.77$, Fig. 1f). In addition, the decreasing trends from harvest to 8 months in storage were significant ($p < 0.05$) at all three temperatures (Fig. 1d, e, f). Likewise, larger seasonal variations were observed at 5.6 °C than at 7.2 °C and 8.9 °C storage temperatures, because ranges in sucrose levels (maximum minus minimum) over the 8-month storage seasons at 5.6, 7.2 and 8.9 °C were 0.064, 0.041, and 0.034%FW separately (Table 3). Average sucrose content across the 15 seasons at 5.6 °C was significantly higher than at 7.2 and at 8.9 °C ($p < 0.05$, Table 3).

Photovolt Reflectance (Fry Color), Mottling Severity, and Sugar End Defect

Effects of year, temperature, storage duration, and two-way interactions on photovolt reflectance, indicating fry color, and mottling severity were significant at the $\alpha = 0.05$ level, but the three-way interactions were not significant (Table 1).

After the first two months at storage, average reflectance readings of French fries from tubers stored at 5.6 °C were consistently lower, indicating darker fry color, than values of tubers stored at 7.2 °C and 8.9 °C (Fig. 1g, h, i). During the first three months after harvest, average reflectance readings at all three storage temperatures decreased to a minimum, with the decline at 5.6 °C being the greatest ($p < 0.05$), and thereafter increased until the end of the storage season (Fig. 1g). The increases in photovolt readings from 3 to 8 months were significant at all three temperatures (Fig. 1g, h, i). Seasonal variation in fry color was greater at 5.6 °C than at 7.2 and 8.9 °C, as indicated by the ranges in photovolt readings under each temperature (Table 4). Average fry color across years at 5.6 °C was significantly the darkest, followed by 7.2 °C, and was the lightest at 8.9 °C ($p < 0.05$, Table 4). It is notable that across the three storage temperatures during the 2011–12, 2012–13, and 2013–14 seasons, tubers produced the darkest French fries ($p < 0.05$, Table 4).

Mottling severity was variable across storage seasons, and there were larger seasonal variations at 5.6 °C and 7.2 °C than at 8.9 °C (Table 5). Mottling severity of tubers from the 2011–12 storage season across the three storage temperatures was among the significantly highest values compared with the other seasons ($p < 0.05$, Table 5). There was a significant trend that mottling severity increased during the first two months in storage at 5.6 °C ($p < 0.05$), and remained constant until the end of storage (Fig. 1j). A similar trend was observed at 7.2 °C,

Table 1 ANOVA table for glucose and sucrose content, photovolt reflectance (fry color), and mottling severity

Source of variance	df	Mean square		df	Mean square	
		Glucose	Sucrose		Fry color	Mottling
Year	14	0.092***	0.012***	10	534.3**	2.689***
Time	8	0.064***	0.028***	8	1210.2***	4.253***
Temp[§]	2	0.613***	0.121***	2	1913.8***	39.542***
Time*Temp	16	0.014***	0.004***	16	338.2*	1.242***
Year*Time	106	0.003***	0.001***	73	241.6	0.443***
Year*Temp	28	0.011***	0.001***	20	370.8**	0.454***
Year*Time*Temp	212	0.001***	0.003***	146	171.2	0.108

*Significant at $\alpha = 0.05$

**Significant at $\alpha = 0.01$

*** Significant at $\alpha = 0.001$

: Months in storage

[§] : Storage temperature

although the magnitude of change was smaller (Fig. 1k). At 8.9 °C, the severity of mottling did not significantly change over the eight months of storage, and stayed at a very low level (Fig. 1l). Overall, Russet Burbank did not exhibit extensive mottling in storage over the trial seasons (Table 5).

Figure 2 shows an approximate 10-day period with the daily average temperature higher than 25 °C in late June and early July of the 2011–2012 and 2013–2014 seasons, indicating warmer days and nights. In comparison, during the same period of the 1999–2000 and 2009–2010 seasons depicting consistently lower average tuber glucose content and lighter fry color ($p < 0.05$, Table 2 and 4), average daily temperatures were lower than 21 °C (Fig. 2). Average sugar end defect incidence at harvest was 53 and 87 % in 2011–12 and 2013–14 respectively, and was 13 and 33 % in 1999–2000 and 2009–10 respectively.

Approximate Dormancy Length

The average dormancy length for Russet Burbank over the 15 storage seasons was 178 days at 5.6 °C, 154 days at 7.2 °C, and 136 days at 8.9 °C, which were significantly different from each other (Table 6). Dormancy length at 5.6 °C was relatively stable at around 175 days for the first 11 seasons (1999–2000 to 2009–2010), but were 187 days or above from 2010 to 2014 (Table 6). Dormancy length at 7.2 °C ranged from 132 days (2009–2010) to 178 days (2011–2012) (Table 6). Values at 8.9 °C ranged from 125 days (2009–2010) to 158 days (2011–2012) (Table 6). Dormancy length was the longest in the 2011–12 season ($p < 0.05$, Table 6).

Specific Gravity and Weight Loss

Specific gravity at harvest ranged from 1.071 to 1.081 across 9 years and there was no significant year effect (Table 7).

Average percent fresh weight loss of Russet Burbank over the eight-month storage duration was 6.1 %, with loss in the 2012–2013 season significantly higher than most of the other seasons ($p < 0.05$, Table 7).

Discussion

This study provides some perspectives on Russet Burbank responses to consistent storage strategies and the effects of growing conditions on those strategies over many years. Information from the study should provide valuable guidance for future storage quality management of Russet Burbank, and also provide a useful reference for optimizing storage management of new varieties.

Year effect was significant on all of the storage quality characteristics measured in this study ($p < 0.001$, Table 1). There were three major factors that may have interacted to affect post-harvest quality in this study: agronomic practices, environmental conditions during the growing season, and storage conditions. Since agronomic practices and storage conditions in this study remained similar over the seasons, year effect may be more strongly associated with different environmental (i.e. weather) conditions during the growing season. Weather factors such as rainfall, daytime and nighttime air and soil temperatures, were inconsistent across years, and this can lead to variable tuber growth, starch accumulation, and other physiological properties of the potatoes at harvest and in storage (Brandt et al. 2009). For example, a transitory period of drought and heat stress during the early tuber bulking stage can cause starch reduction and reducing sugar accumulation on the stem end portion of tubers at harvest, resulting in unacceptable discolored French fries after processing (Thornton et al. 2010). This problem is called sugar end defect, and it cannot be mitigated after potatoes are placed into storage

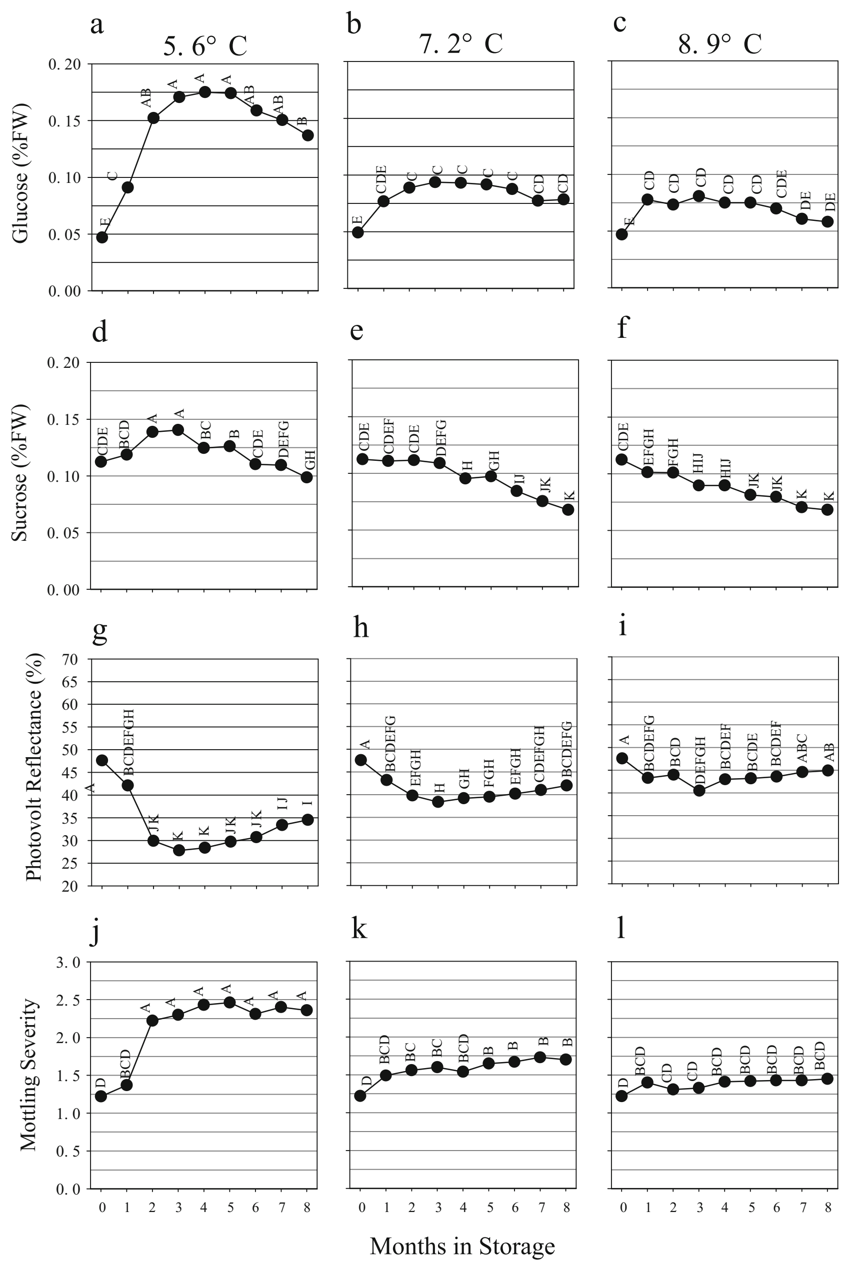

Fig. 1 Glucose content (%FW) (**a**, **b**, **c**), sucrose content (%FW) (**d**, **e**, **f**), photovolt reflectance reading (fry color) (**g**, **h**, **i**), and mottling severity (**j**, **k**, **l**) of Russet Burbank tubers stored for 8 months (each month indicated by a *dot*) at 5.6 °C, 7.2 °C, and 8.9 °C. Dots followed by different letters are significantly different at $\alpha = 0.05$. Glucose and sucrose values at each monthly sampling are the mean across 15 storage seasons (1999–2000 to 2013–2014). Fry color and mottling severity values at each monthly sampling are the mean over 11 storage seasons (2003–2004 to 2013–2014)

(Thompson et al. 2008). It has been reported that Russet Burbank is susceptible to sugar end defect (Love et al. 2003). The generally higher average tuber glucose, dark fry color, high mottling severity across all the three storage temperatures in the 2011–2012 and 2013–2014 seasons (Table 2, 4 and 5) could be potentially attributed to a short period of high daytime temperature (>32 °C) during early tuber development (Fig. 2). Weather is not controllable, but effective production management responses to weather changes, such as effectively monitoring in and between proper timing of irrigation, developing an extensive healthy root system to ensure sufficient water and nutrients uptake, having sufficient canopy to cover the soil surface and moderate soil temperature, can ameliorate potential losses caused by environmental stresses.

Temperatures between 7.2 and 8.9 °C appeared to be a good range for storing Russet Burbank potatoes for frozen processing. Storage at 5.6 °C resulted in significant increases of sucrose and glucose ($p < 0.05$) at the beginning of the storage season (including the wound healing period), darker fry color, and more severe mottling, compared to storing at 7.2 and 8.9 °C (Fig. 1, Tables 2 and 3). This could be explained by development of LTS at 5.6 °C, where reducing sugars accumulated through cold-induced catabolism of starch (Isherwood 1976), synthesis of sucrose (Viola et al. 1991), and its subsequent hydrolysis under the enzyme activity of vacuolar acid invertase (Matsuuro-Endo et al. 2004). Higher glucose content leads to more severe discoloration after tubers are processed into French fries (Driskill et al. 2007).

Table 2 Average glucose content (%FW) in each storage season (1999–2000 to 2013–2014) under the three temperatures

Year	Temperature			Mean across temperatures	
	5.6 °C	7.2 °C	8.9 °C		
1999–2000	0.098	0.057	0.056	0.071	FGH
2000–2001	0.104	0.063	0.059	0.077	EFGH
2001–2002	0.093	0.040	0.034	0.057	H
2002–2003	0.074	0.056	0.045	0.059	H
2003–2004	0.117	0.066	0.055	0.079	EFG
2004–2005	0.133	0.045	0.038	0.074	FGH
2005–2006	0.132	0.119	0.082	0.089	DEF
2006–2007	0.201	0.116	0.106	0.142	B
2007–2008	0.132	0.069	0.081	0.095	CDE
2008–2009	0.169	0.093	0.076	0.113	C
2009–2010	0.087	0.057	0.045	0.064	GH
2010–2011	0.231	0.116	0.082	0.143	B
2011–2012	0.259	0.131	0.105	0.166	A
2012–2013	0.153	0.091	0.082	0.109	CD
2013–2014	0.250	0.123	0.091	0.145	AB
Range	0.074–0.259	0.040–0.131	0.034–0.106		
LSD ($\alpha = 0.05$)	0.058				
Mean across years	0.146 a	0.082 b	0.068 c		

Range of values under each temperature and LSD at the $\alpha = 0.05$ level between every temperature by year combination were listed under the temperature column. Mean values across temperatures are indicated by a separate column. Mean values across years are indicated by a separate row. Numbers followed by different letters are significantly different at $\alpha = 0.05$

Table 3 Average sucrose content (%FW) in each storage season (1999–2000 to 2013–2014) under the three temperatures

Year	Temperature			Mean across temperatures	
	5.6 °C	7.2 °C	8.9 °C		
1999–2000	0.100	0.088	0.077	0.089	DE
2000–2001	0.088	0.073	0.065	0.075	F
2001–2002	0.124	0.094	0.092	0.103	C
2002–2003	0.120	0.099	0.089	0.103	C
2003–2004	0.131	0.097	0.097	0.108	ABC
2004–2005	0.152	0.109	0.091	0.118	A
2005–2006	0.128	0.100	0.099	0.109	ABC
2006–2007	0.118	0.091	0.091	0.101	CD
2007–2008	0.100	0.078	0.078	0.086	EF
2008–2009	0.119	0.100	0.092	0.104	BC
2009–2010	0.114	0.101	0.085	0.100	CD
2010–2011	0.129	0.106	0.091	0.109	ABC
2011–2012	0.129	0.095	0.079	0.102	C
2012–2013	0.140	0.114	0.092	0.117	AB
2013–2014	0.144	0.107	0.097	0.117	AB
Range	0.088–0.152	0.073–0.114	0.065–0.099		
LSD ($\alpha = 0.05$)	0.024				
Mean across years	0.123 a	0.097 b	0.088 c		

Range of values under each temperature and LSD at the $\alpha = 0.05$ level between every temperature by year combination were listed under the temperature column. Mean values across temperatures are indicated by a separate column. Mean values across years are indicated by a separate row. Numbers followed by different letters are significantly different at $\alpha = 0.05$

Table 4 Average photovolt reading in each storage season (2003–2004 to 2013–2014) under the three temperatures

Year	Temperature			Mean across temperatures	
	5.6 °C	7.2 °C	8.9 °C		
2003–2004	38.4	43.1	47.4	43.0	A
2004–2005	35.9	46.3	49.9	44.1	A
2005–2006	38.8	43.2	47.8	43.2	A
2006–2007	32.2	40.5	41.9	38.2	B
2007–2008	38.0	44.5	43.3	41.9	A
2008–2009	32.6	41.3	43.4	39.1	B
2009–2010	37.2	44.2	45.7	42.4	A
2010–2011	30.3	39.9	43.9	38.0	B
2011–2012	24.5	36.4	41.1	34.0	C
2012–2013	29.6	36.8	38.0	34.8	C
2013–2014	26.9	35.0	38.1	33.3	C
Range	24.5–38.8	35.0–46.3	38.0–49.9		
LSD ($\alpha = 0.05$)	5.5				
Mean across years	33.1 c	41.0 b	43.7 a		

Range of values under each temperature and LSD at the $\alpha = 0.05$ level between every temperature by year combination were listed under the temperature column. Mean values across temperatures are indicated by a separate column. Mean values across years are indicated by a separate row. Numbers followed by different letters are significantly different at $\alpha = 0.05$

Therefore, storing Russet Burbank potatoes at a higher temperature (>7 °C) is important for maintaining long-term storability. If stored at temperatures below 7 °C, tubers accumulate sugars and also develop a poorer texture than those

Table 5 Average mottling severity in each storage season (2003–2004 to 2013–2014) under the three temperatures

Year	Temperature			Mean across temperatures	
	5.6 °C	7.2 °C	8.9 °C		
2003–2004	1.9	1.3	1.1	1.5	EF
2004–2005	2.0	1.5	1.2	1.6	DEF
2005–2006	1.7	1.2	1.1	1.3	F
2006–2007	2.0	1.5	1.3	1.6	CDE
2007–2008	2.0	1.5	1.4	1.6	CDE
2008–2009	2.6	1.7	1.6	2.0	A
2009–2010	2.2	1.6	1.3	1.7	BCD
2010–2011	2.3	1.8	1.3	1.8	ABC
2011–2012	2.7	1.9	1.3	2.0	A
2012–2013	2.2	1.8	1.6	1.9	AB
2013–2014	2.0	1.8	1.5	1.8	ABCD
Range	1.7–2.7	1.3–1.9	1.1–1.6		
LSD ($\alpha = 0.05$)	0.5				
Mean across years	2.2 a	1.6 b	1.4 c		

Range of values under each temperature and LSD at the $\alpha = 0.05$ level between every temperature by year combination were listed under the temperature column. Mean values across temperatures are indicated by a separate column. Mean values across years are indicated by a separate row. Numbers followed by different letters are significantly different at $\alpha = 0.05$

1 = no mottling

2 = mild mottling

3 = moderate mottling

4 = severe mottling

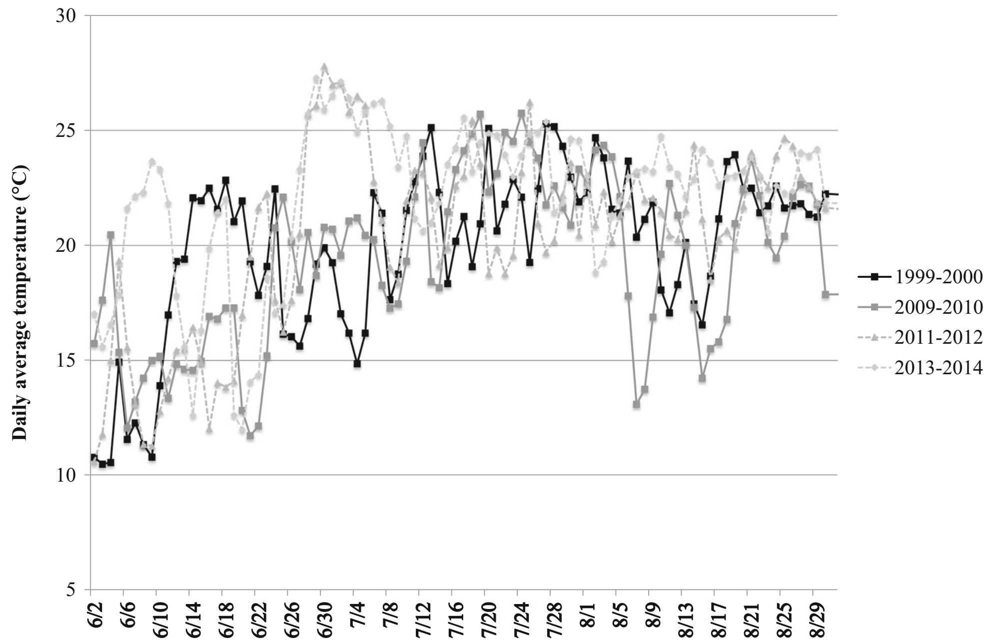

Fig. 2 Daily average temperature (°C) during June, July and August of the 2011–2012 (*dashed grey line*) and 2013–2014 (*dashed light grey line*) seasons of tubers with high glucose content and dark fry color, and of the 1999–2000 (*solid black line*) and 2009–2010 (*solid grey line*) seasons of tubers with low glucose content

stored at higher temperatures (Iritani and Sparks 1985). Tubers stored at significantly higher temperatures tend to lose more weight and storage quality does not improve (Iritani and Sparks 1985). Average dormancy length was significantly different at each storage temperature. It was the shortest at 8.9 °C and the longest at 5.6 °C storage temperature, suggesting that efficient application of sprout inhibitor prior to dormancy break under the warmer storage temperature is important.

Larger year to year variations in tuber glucose and sucrose concentrations in storage were observed at 5.6 °C than at the

Table 6 Average approximate dormancy length (days after harvest) of Russet Burbank tubers (without the application of CIPC) in each storage season (1999–2000 to 2013–2014) under the three temperatures

Year	Temperature			Mean across temperatures	
	5.6 °C	7.2 °C	8.9 °C		
1999–2000	175	140	135	150	EFG
2000–2001	173	153	132	153	DEF
2001–2002	172	135	127	144	FG
2002–2003	177	152	132	153	DEF
2003–2004	173	145	150	156	CDE
2004–2005	178	167	133	159	BCDE
2005–2006	181	160	128	157	CDE
2006–2007	167	148	138	151	EFG
2007–2008	168	153	138	153	DEF
2008–2009	178	147	128	151	EFG
2009–2010	168	132	125	142	G
2010–2011	187	165	133	162	BCD
2011–2012	197	178	158	178	A
2012–2013	188	163	151	167	B
2013–2014	187	165	137	163	BC
Range	167–197	132–178	125–158		
LSD ($\alpha = 0.05$)	20				
Mean across years	178 a	154 b	136 c		

Range of values under each temperature and LSD at the $\alpha = 0.05$ level between every temperature by year combination were listed under the temperature column. Mean values across temperatures are indicated by a separate column. Mean values across years are indicated by a separate row. Numbers followed by different letters are significantly different at $\alpha = 0.05$

Table 7 Specific gravity and percent weight loss (%FW) of Russet Burbank potatoes over 9 storage seasons (2005–2006 to 2013–2014)

Year	Specific gravity		Weight loss (%FW)	
2005–2006	1.079	A	5.2	c
2006–2007	1.081	A	5.5	c
2007–2008	1.071	A	5.7	c
2008–2009	1.073	A	5.0	c
2009–2010	1.076	A	5.1	c
2010–2011	1.079	A	5.1	c
2011–2012	1.076	A	6.4	bc
2012–2013	1.072	A	9.1	a
2013–2014	1.071	A	7.8	ab

Numbers followed by the same letters are not significantly different at $\alpha = 0.05$

other two temperatures (Tables 2 and 3). Sucrose and glucose content of tubers at harvest varied each year due to conditions unique to each growing season, which influences the development of sugar end defect and other sweetening defects (Bussan et al. 2009). During storage at 5.6 °C, sucrose is converted to reducing sugars with potential further starch breakdown, resulting in variable levels of glucose and sucrose in tubers during storage at 5.6 °C between years (Fig. 1a, d). In comparison, sucrose declined in tubers over the 8-month storage period at 7.2 °C and 8.9 °C ($p < 0.05$, Fig. 1e, f), whereas glucose remained relatively constant (Fig. 1b, c). This suggests that at higher storage temperatures (>7 °C), sucrose is consistently consumed for tuber respiration, and thus no net accumulation of glucose occurred during this process, causing less variability in glucose concentration over years. Tuber respiration rate during storage is temperature dependent. Respiration is typically at the lowest point at 5 °C, and increases at higher temperature (Stevenson et al. 2001). Further study is needed to investigate change of respiration rates for Russet Burbank potatoes under the three storage temperatures over the eight-month storage duration and relate to concurrent quality changes.

Acknowledgments The authors thank Dr. Gale Kleinkopf, an emeritus professor at the Kimberly R&E Center of University of Idaho, for initiating this study, and support staff at KREC for providing field and lab work assistance. The authors also thank the Idaho Potato Commission and Northwest Potato Consortium for providing funds for the project.

References

Amer, F.S., L. Reddivari, G.P. Madiwale, M. Stone, D.G. Holm, and J. Vanamala. 2014. Effect of genotype and storage on glycoalkaloid and acrylamide content and sensory attributes on potato chips. *American Journal of Potato Research* 91: 632–641.

Bethke, P. 2014. Ethylene in the atmosphere of commercial potato (Solanum tuberosum) storage bins and potential effects on tuber respiration rate and fried chip color. *American Journal of Potato Research* 91: 688–695.

Boe, A., G. Woodbury, and T. Lee. 1974. Respiration studies on Russet Burbank potato tubers—effects of storage temperature and chemical treatments. *American Potato Journal* 51: 355–360.

Bogucki, S., and D. Nelson. 1980. Length of dormancy and sprouting characteristics of 10 potato cultivars. *American Potato Journal* 57: 151–157.

Brandt, T., Olsen, N., and Kleinkopf, G. 2009. Effect of growing season on 'Russet Burbank' storage tuber quality. *American Journal of Potato Research* 86: 138.

Bussan, A., R. Sabba, and M. Drilias. 2009. *Tuber maturation and potato storability: optimizing skin set; sugars; and solids*. Madison: University of Wisconsin-Extension, Cooperative extension.

Castleberry, H., and Jayanty, S. 2012. An experimental study of pressure flattening during long-term storage in four russet potato cultivars with differences in at-harvest tuber moisture loss. *American Journal of Potato Research* 89: 269–276.

Coleman, W., Li, X., Tremblay-Deveau, E., and Coleman, S. 2003. Chemical maturation and storage performance of eleven Russet Burbank clones. *Canadian Journal of Plant Science* 83: 893–902.

Cunningham, H., M. Zaehring, and W. Sparks. 1971. Storage temperature for maintenance of internal quality in Idaho Russet Burbank potatoes. *American Potato Journal* 48: 320.

Daniels-Lake, B., R.J.N. Prange, S. Asiedu, and J. Walsh. 2005. Sprout development and processing quality changes in potato tubers stored under ethylene: 1. effects of ethylene concentration. *American Journal of Potato Research* 82: 389–397.

Driskill, E., Knowles, L., and Knowles, N. 2007. Temperature-induced changes in potato processing quality during storage are modulated by tuber maturity. *American Journal of Potato Research* 84: 367–383.

Foukaraki, S., Cools, K., Chope, G., and Terry, L. 2014. Effect of the transition between ethylene and air storage on post-harvest quality in six UK-grown potato cultivars. *Journal of Horticulture Science Biotechnology* 89: 599–606.

Iritani, W., and W. Sparks. 1985. Potatoes storage and quality maintenance in the Pacific Northwest. Cooperative Extension of Washington State University.

Iritani, W., and L. Weller. 1976. Influence of early storage (pre-holding) temperatures on sugar accumulation in Russet Burbank potatoes. *American Potato Journal* 53: 159–167.

Isherwood, F. 1976. Mechanism of starch-sugar interconversion in Solanum tuberosum. *Phytochemistry* 15: 33–41.

Kincaid, D., Westermann, D., and Trout, T. 1993. Irrigation and soil temperature effects on Russet Burbank quality. *American Potato Journal* 70: 711–723.

Kleinkopf, G., and Olsen, N. 2003. Storage management. In J. Stark, & S. Love, *Potato production systems* (p. 369). Moscow, ID: University of Idaho Agricultural Communications.

Kleinkopf, G., Westermann, D., Wille, M., and Kleinschmidt, G. 1987. Specific gravity of Russet Burbank potatoes. *American Potato Journal* 64: 597–587.

Kyriacou, M., Ioannides, I., Gerasopoulos, D., and Siomos, A. 2009. Storage profiles and processing potential of four potato (Solanum tuberosum L.) cultivars under three storage temperature regimes. *Journal of Food Agriculture Environ*ment 7: 31–37.

Lammerink, J. 1989. Response of the processing quality of ptoato cultivars to long-term storage conditions. *New Zealand Journal of Crop Horticulture Science* 17: 61–65.

Love, S., R. Novy, D. Corsini, and P. Bain. 2003. Variety selection and management. In *Potato production systems*, eds. Stark J., and S. Love, 29. Moscow, ID: University of Idaho Agricultural Communications.

Matsuuro-Endo, C., kobayashi, A., Noda, T., Takigawa, S., Yamauchi, H., and Mori, M. 2004. Changes in sugar content and activity of vacuolar acid invertase during low-temperature storage of potato tubers from six Janpanese cultivars. *Journal of Plant Research* 117: 131–137.

Muttucumaru, N., Powers, S., Elmore, J., Mottram, D., and Halford, N. 2015. Effects of water availability on free amino acids, sugars, and acrylamide-forming potential in potato. *Journal of Agricultural Food Chemistry* 63: 2566–2575.

Rak, K., F. Navarro, and J. Palta. 2013. Genotype × storage environment interaction and stability of potato chip color: implications in breeding for cold storage chip quality. *Crop Science* 53: 1944–1952.

Rommens, C., Ye, J., Richael, C., and Swords, K. 2006. Improving potato storage and processing characteristics through all-native DNA transformation. *Journal of Agricultural Food Chemistry* 54: 9882–9887.

Schippers, P. 1971. The relation between storage conditions and changes in weight and specific gravity of potatoes. *American Potato Journal* 48: 313–319.

Sonnewald, S., and Sonnewald, U. 2014. Regulation of potato tuber sprouting. *Planta* 239: 27–38.

Sparks, W. 1973. Influence of ventilation and humidity during storage on weight and quality changes of Russet Burbank potatoes. *Potato Research* 16: 213–223.

Stark, J., and S. Love. 2003. *Potato production systems*. Moscow: University of Idaho Press.

Stevenson, W., R. Loria, G. France, and D. Weingartner. 2001. *Compendium of potato diseases*. St Paul: The American Phytopathological Society.

Thompson, A., S. Love, J. Sowokinos, M. Thornton, and C. Shock. 2008. Review of the sugar end disorder in potato (Solanum tuberosum, L.). *American Journal of Potato Research* 85: 375–386.

Thornton, M., W. Buhrig, and N. Olsen. 2010. The relationship between soil temperature and sugar ends in potato. *Potato Research* 53: 289–296.

USDA, NASS-Northwest Regional Field Office 2014. Potato variety. Olympia, WA.

Viola, R., Davies, H., and Chdek. 1991. Pathway of starch and sucrose biosynthesis in developing tubers of potato (Solanum tuberosum L.) and seeds of faba bean (Vicia faba L.). Elucidation by 13C NMR spectroscopy. *Planta* 183: 202–208.

Yang, J., J. Powers, T. Boylston, and K. Weller. 1999. Sugars and free amino acids in stored Russet Burbank potatoes treated with CIPC and alternative sprout inhibitors. *Journal of Food Science* 64: 592–596.

Zaehringer, M., Cunningham, H., and Sparks, W. 1966. Sugar content and color of Russet Burbank potatoes as related to storage temperature and sprout inhibitors. *American Potato Journal* 43: 305–314.

Zommick, D., L. Knowles, M. Pavek, and N. Knowles. 2014. In-season heat stress compromises postharvest quality and low-temperature sweetening resistance in potato (Solanum tuberosum L.). *Planta* 239: 1243–1263.