



Susceptibility to Pressure Flattening Correlates with Texture Analysis of Potato Tubers

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Abstract The physiological disorder referred to as pressure flattening is a cause of significant economic losses in the storage of Irish potatoes (*Solanum tuberosum* L.) intended for use in the fresh market. As the flattened area on each tuber becomes larger in diameter or becomes more depressed the USDA quality grade, and therefore the market value of the potatoes is reduced. Experiments were conducted to identify at-harvest which potato lots within and among cultivars were likely to pressure flatten earlier or more severely. The use of an instrumented penetrometer or texture analyzer to measure peak load required for periderm deformation at harvest appears to anticipate correctly the majority of fields from which tubers are more likely to have severe pressure flattening at six months' storage duration. At-harvest texture analysis appears to segregate varieties according to susceptibility to deformation based on cultivar specific factors that play a role in pressure flattening development during storage. The Pearson correlation coefficient ($R^2=0.5481$) indicates that there is a correlation between tuber texture at harvest and pressure flattened area on the tuber following storage. Testing of tubers from different fields and cultivars as the potatoes are loaded into storage, may allow growers to identify and ship potatoes that are more susceptible before they develop significant pressure flattening.

Resumen El desorden fisiológico referido como despresurización, es causa de pérdidas económicas significativas en el almacenamiento de la papa irlandesa (*Solanum tuberosum*

L.) cuya intención de uso es en el mercado fresco. A medida que el área desinflada de cada tubérculo se agranda en diámetro, o se vuelve más deprimida, la calificación USDA, y por lo tanto el valor en el mercado de las papas, se reduce. Se condujeron experimentos para identificar a la cosecha que lotes de papa, dentro y entre variedades, era probable que se desinflaran más pronto o más severamente. El uso de un penetrómetro instrumentado o un analizador de textura para medir la carga máxima requerida para la deformación del peridermo a la cosecha, parece anticipar correctamente a la mayoría de los campos de los cuales los tubérculos era más probable que tuvieran desinflamiento severo a los seis meses de duración del almacenamiento. A la cosecha, el análisis de la textura parece segregar a las variedades de acuerdo a la susceptibilidad a la deformación con base en factores específicos de la variedad que juegan un papel en el desarrollo de la despresurización durante el almacenamiento. El coeficiente de correlación de Pearson ($R = 0.5481$) indica que hay una correlación entre la textura del tubérculo a la cosecha y el área desinflada en el tubérculo después del almacenamiento. Probando tubérculos de diferentes campos y variedades cuando las papas son cargadas al almacenamiento pudiera permitir a los productores identificar y enviar papas que son más susceptibles antes de que desarrollen despresurización significativa.

Keywords *Solanum tuberosum* · Potato bruise · Potato storage

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Introduction

The physiological disorder pressure flattening is a major cause of economic losses in bin stored potato crops (Baritelle et al. 2000). Long-term storage of up to 12 months is necessary to provide a year-round supply of potatoes to the market. The

disorder is also frequently referred to as pressure bruising, although not all pressure flattened areas and not all cultivars readily produce the darkened “bruise” discoloration under affected areas of skin (Lulai et al. 2000). Pressure flattening refers to the development of depressed or sunken areas on stored tubers surface (Rowe 1993) as it becomes depressed or flattened due to constant contact with a portion of an adjacent tuber. This area of contact also receives the force exerted by the adjacent tuber as a result of the weight of tubers above it in a pile. The downward force or pile pressure is approximated as 672 kg/m^3 of the pile above the potato (Muthukumarappan et al. 1994). The area of greatest pressure flattening is approximately 1–2 m from the floor due to the pressure of piled potatoes above and the distribution of ventilation air. This also corresponds to the area of maximum lateral pressure from the pile (Matson and Hellickson 1983).

Pressure flattening accounts for a substantial portion of the \$298 million dollars in losses due to potato bruising each storage year (Baritelle et al. 2000; Baritelle and Hyde 2003). Losses are more severe for pressure bruised or pressure flattened potatoes intended for the fresh market potato sales. However, pressure flattening accompanied by discoloration of the underlying tissue is a major concern for chipping and processing users as well. The development of discoloration below the surface can reduce quality grade and may not develop until up to 5 days after the potatoes are first unloaded (personal communication, Behil, K.). This is thought to be due to limited oxygen availability to the damaged area, as described by Busch (1999). The severity of pressure flattening losses is often not apparent until the potatoes are removed from storage.

Economic losses are usually a result of the reduction in the quality grade assigned to shipped tubers due to pressure flattened tubers. Pressure flattening often results in shipments that would have quality sufficient to be sold as USDA No.1 downgraded to USDA No. 2 or lower. This often reduces returns to potato grower and shippers by 40% or more. By late spring, some lots of potatoes may have as much as 70% of tubers with pressure flattening (Allen 2009). This can result in half a bin of potatoes being thrown away, or sold for processing, in order to meet a grade standard desired by a fresh market buyer.

Growers must determine which potatoes to unload from storage first and which potatoes will store with the least amount of loss if kept until the end of their storage season. We decided if an at-harvest or early storage season test could determine which fields or cultivars were more likely to pressure flatten first, it would help growers schedule a shipping order that could reduce their economic losses. This would be accomplished by early storage season shipping of the most pressure flattening susceptible fields and cultivars while allowing less susceptible fields to be shipped later. An initial step in determining whether to consider an at-harvest testing

methodology to predict pressure flattening would be to identify variability among and within cultivars with regard to the factor being tested. Secondly, there was a need to correlate data from these at-harvest tests with the amount of pressure flattening observed after a common storage duration. The at-harvest predictive test we have used involves the measurement of the maximum amount of force required to deform the surface of the tubers. This method would be similar to testing using a penetrometer test with apples to determine storability (Brennan et al. 1977; Abbott et al. 1984). The use of a penetrometer had been shown to accurately determine differences in tuber moisture content (Sharrock 1968). Other research determined differences in the resistance of potato tissue to force and pressure were based on cultivar differences and tuber hydration (Zdunek and Umeda 2005; Bajema et al. 1998). Following testing of rheological properties, Zhu (2003) theorized that greater resistance to load might be based on cells being relatively unable to gradually leak contents unless the cells fully rupture. Cellular rupture is especially likely to occur if cellular adhesion is strong. There are many complex factors that make up the response of plant tissue to pressure, including cellular turgor, cell wall properties, elastic properties of the tissue, and structural arrangement of the tissue.

However, the use of a penetrometer or texture analyzer to predict relative pressure flattening of stored potatoes was considered a novel concept. The goal of this research project was to determine if an at-harvest test could identify differences in pressure flattening development among cultivars believed to be more and less susceptible to pressure flattening development and if testing could identify tubers that may be more dehydrated at harvest and therefore more prone to pressure flattening.

Materials and Methods

Penetrometer Analysis

A texture analyzer or instrumented penetrometer was used to determine peak load required for surface tissue deformation. Initial testing was conducted using Brookfield 10 kg. equipped with a TA-Bt kit and a T18 spherical probe (Brookfield Engineering Laboratories, Inc. Middleboro, MA, USA). The TA-Bt Kit is an adjustable flat metal sample table that holds a sample below a descending probe fixture (in this case, a 12 mm. spherical steel ball, the T18 probe). The spherical probe was considered the most analogous to the rounded surface of an adjacent tuber. The 3 mm. target deformation depth correspond well to the depth of the periderm and underlying cells that would be crushed by pressure flattening in commercial storage. The tubers were tested using the instrument by cutting them in half and setting the half, cut side

down, on top of the fixture table. The instrument was set for the probe to descend at 0.5 mm. per second until contact with the tuber surface resulted in a force load of 75 g., at which point the instrument recorded the force applied every one-tenth of a second. This continued until the probe was 3 mm. below the 75-g “trigger” setting. Once 3 mm. deformation has achieved the probe ascended at 5 mm. per second post-test speed. The highest force applied, the “peak load” in grams was recorded separately, averaged, and used to compare the different cultivars and treatments. The instrument was first tried on Rio Grande Russet storage tubers and oven treated tuber samples, with and without removing the periderm by peeling. This experiment was conducted in order to determine if the tuber periderm and moisture loss had an effect on the peak load required for deformation. In 2011 and 2012 penetrometer analysis was conducted using a 25 kg. capacity Brookfield CT3 Texture Analyzer equipped with same setup and fixtures as the 10 kg. model. For these samples, the tuber surface was not peeled because the previous testing determined that the skin (outer periderm) itself provide some resistance to deformation under pressure, as well as because potatoes in bulk storage are stored with their skin attached.

Testing to Determine Instrument Sensitivity to Differences in Tuber Hydration

In 2011 and 2012, additional penetrometer testing was done using tubers of 3 russet cultivars (Russet Norkotah Selection 8, Classic, and Rio Grande Russet) to determine the sensitivity of the texture analyzer to moisture loss (as percent weight loss) from the tubers. All three varieties were grown in a common plot at the San Luis Valley Research and extension center, receiving standard irrigation and pest control. Plots were planted in early May and vine killed at approximately 130 DAP. Applied nitrogen fertilization was typically 123 kg per hectare, including 67 kg applied before planting. Approximately three hundred tubers (weighing 228–342 g.) of each cultivar were harvested from moist soil by hand and weighed using an analytical balance. The weight of the tubers was then written on that tuber using a black permanent marker. The tubers were then stored in groups by cultivar in 35 l plastic buckets under ambient conditions (20 °C and 40% relative humidity) and re-weighed twice a day. As the tubers lost weight, the tubers were separated into groups based on half-percent moisture loss intervals ($\pm 0.15\%$) until a group of twenty tubers was created for each group. In other words, as each of the 300 potatoes for each cultivar were reweighed, the amount of weight loss was immediately calculated for that tuber. If a tuber had lost between 0.35% and 0.65%, it was put in a group of potatoes that had lost roughly 0.5%. Once twenty tubers were found at an individual re-weighing that had lost 0.5%, that set of tubers was considered to be complete for that cultivar. The twenty tubers were then evaluated using

the texture analyzer to determine peak load required for 3 mm. deformation and tested for relative water content. Extra tubers were returned to the buckets so that twenty tubers could be identified at subsequent weighing that had lost 1% of their weight and so on until twenty tubers with 4% moisture loss had been tested. Although only 180 tubers were used for each cultivar, 300 tubers were initially harvested. This was done because many tubers at each weighing would not fall within $\pm 0.15\%$ of a weight loss category, and other tubers would either lose weight much faster or far slower than the majority of the tubers for that cultivar. The same procedure for evaluating pressure flattening versus weight loss was followed in 2012, with an exception that the CT3 texture analyzer used had a 25 kg. capacity for applying a peak load.

Testing of Samples from Multiple Trials and Varieties to Establish Correlation between at Harvest Testing and Post Storage Pressure Flattened Area

Potatoes were selected from field plots grown at the San Luis Valley Research Center and Farming Technologies Inc., Colorado during the 2010, 2011, and 2012 growing seasons. The potato fields received standard irrigation and pest control applications as needed. Applied nitrogen fertilization was typically 120 kg per hectare, including 60–70 kg applied before planting.

Penetrometer analysis was conducted for all treatments and cultivars in field trials in 2011 and 2012, which resulted in 45 separate combinations of cultivars and treatments. Plots were mechanically harvested three weeks after vine kill, and 21 plastic mesh bags were used to collect samples with ten 228–342 g tubers for 3, 6, and 9-month storage duration testing. These samples were put aside for later pressure flattening evaluation using the ventilated container system as described in Castleberry and Jayanty (2012).

Inducing Pressure Flattening and Evaluation of Pile Height

Previously, we developed a ventilated container system to induce pressure flattening in potato tubers (Castleberry and Jayanty 2012). The effects of different simulated pile heights was evaluated in 2012–2013. Tubers from 15 different cultivars were evaluated for peak load required for 3 mm surface deformation at harvest. Six ventilated containers were used, to allow for three different pile heights (3.1 m, 3.7 m, and 4.6 m) at two different storage durations (3 months and 6 months). For each cultivar, five replicates of six tubers were placed in labeled 2 kg. plastic mesh bags and then placed in the sample zone of each ventilated container. The ventilated container system was modified by reducing the amount of water in the plastic tank above the container that was used to provide additional weight. The differences in the fill level of the tanks

allowed for pressures on the samples to change, creating the different simulated pile heights.

Evaluation of the Samples for Pressure Flattening

Pressure flattening was evaluated for each tuber within every sample bag. Tubers were visually inspected as soon as possible after removal from the storage containers, and each flattened area was circled, numbered in ascending order using permanent markers, and its diameter measured. Individual flattened areas were measured and averaged for each sample bag, with the number of bags serving as replicates. Pressure flattening from those experiments is presented as the averaged pressure flattened area per tuber. Counting the number and measuring the individual diameter of each bruised area enabled estimation of the USDA grade for each tuber. For example, USDA potato grade standards specify that a 227–340 g tuber which has more than 18 cm² combined flattened area is beyond the grade tolerances established for a US No. 1 or US No. 2 potato. Potatoes were stored at typical commercial storage conditions at 3–4 °C with 95% relative humidity. Storages used in this study were intended for seed potatoes and were not treated with sprout inhibitors.

Cultivar Susceptibility Methodology

Five cultivars that had been planted during 2011 and 2012 growing seasons at a farm and storage operated by a private company were evaluated for relative pressure flattening development. Three specialty cultivars (Asterix, Satina, and Yukon Gold) and two russet cultivars (Innovator, and Russet Norkotah) were evaluated, using samples obtained during bin loading. These varieties were grown under standard irrigation and pest control for approximately 120 DAP, however each variety was grown in a separate field with fertility tailored to that specific variety.

Sixty tubers per cultivar were collected at harvest from field trucks during commercial storage loading and placed inside a climate controlled corridor at approximately 14 °C and 95% relative humidity while samples from the other cultivars were obtained during the next few days. These tubers were then used to create 10, six tuber replicates that were placed in the ventilated container design used to induce pressure flattening. Each year, five replicates were placed in a ventilated container that was unloaded after 3 months and the other five replicates were placed in a ventilated container for 6 months' storage duration.

In 2011, additional samples of thirty tubers of each cultivar were collected from the top of the commercial potato cellar piles one month after harvest and evaluated for differences in the peak load required for 3 mm. surface deformation.

Statistical Analysis and Design

Tubers that were tested or subjected to pressure flattening were randomly selected from among the 227–340 g. tubers from the harvested field or from tubers collected from the research plot trials. The tuber samples placed in the ventilated container design were arranged in randomized fashion within the described sample zone. Data analysis for comparisons among treatments was performed using analysis of variance at $\alpha = 0.05$ using the data analysis ToolPak in Microsoft Excel 2007. Data for individual tubers was averaged within each sample bag. Decayed, diseased, or broken tubers were discarded, and the average for each bag did not include these tubers. The R-squared values displayed in the figures were also calculated by Excel. Error bars in figures and means separation are based on a calculated Fisher's LSD at $\alpha = 0.05$.

Additional analysis was done using SAS 9.3. Test of field variability was done using the method of moments. Test of variety differences was done using REML. The analysis was done using SAS 9.3 for the correlation of peak load required for deformation of multiple varieties and treatments with the resulting pressure flattened area (Pearson correlation coefficients) for the moisture loss by variety versus peak load (two-way ANOVA). Because of the correlations observed, it was decided to compare the averaged pressure flattened area per tuber for the upper half of fields (when organized in order of ascending at-harvest peak load) with the pressure flattened area per tuber from the bottom half of fields after three months of storage. Next, a similar comparison was conducted by organizing the fields and cultivars into quartiles by ascending peak load.

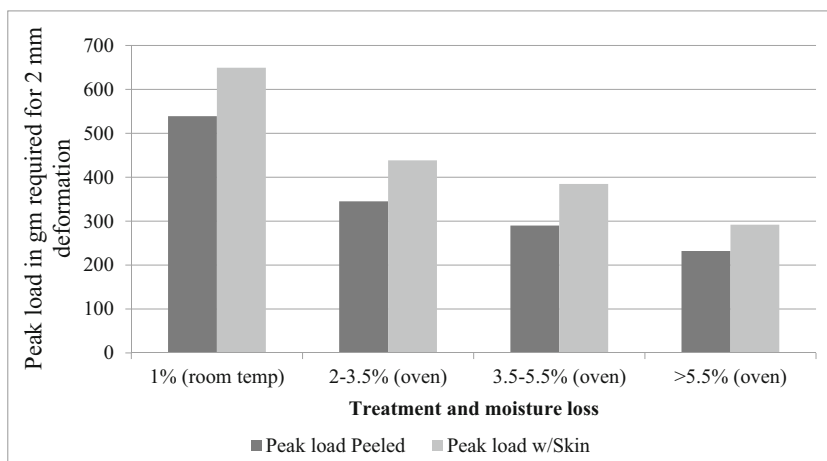
Results

At Harvest Predictive Testing

The results of preliminary testing with the texture analyzer are presented in Fig. 1. The trend of the data indicated that the peak loads required for 2 mm. deformation decreased as moisture loss from the tubers was increased within a cultivar. It also appeared that the skin itself provided some resistance to deformation, and therefore to pressure flattening. The samples were obtained and treated after 5 months of commercial storage which is why the peak load values are much lower than those expected from at-harvest testing.

The texture analyzer was then used in 2011 and 2012 to evaluate the change in peak load required for 3 mm tuber surface deformation as tubers lost weight at 0.5% intervals following harvest from moist soil. In 2011, there was a general trend of decreased peak loads after 1.5% moisture loss across the cultivars tested (Fig. 2). The number of samples out of twenty tubers that were above the maximum peak load

Fig. 1 Change in peak load required for 2 mm tuber surface deformation of post-storage tubers with additional moisture loss treatments. Tubers were tested with skin intact and with skin removed



declined precipitously as weight loss increased from 0.5% to 2.0%.

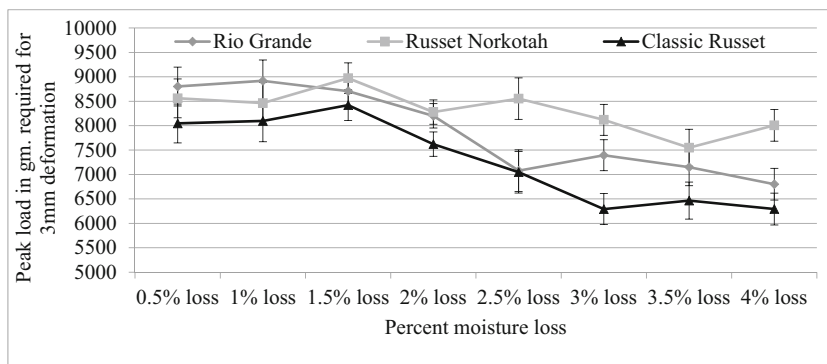
Results of similar testing in 2012 when a 25 kg. capacity CT3 texture analyzer was used show a steady decrease in the peak load required to deform tubers once tubers had lost more than 1% of weight following harvest (Fig. 3). Additionally, in both 2011 and 2012, the cultivar Classic Russet was consistently less resistant to pressure from the texture analyzer which may reflect detectable differences in pressure resistance based on cultivar specific factors in addition to differences resulting from moisture loss.

While it appeared that the texture analyzer could identify differences in pressure flattening susceptibility at harvest, these at-harvest results from the texture analyzer needed to be compared to the amount of pressure flattening after storage. When peak load values at harvest were compared across all the treatments and cultivars used in 2011 field trials (Fig. 4), there were statistically significant differences among the peak

load values at harvest. The samples used were not chosen to make observations about particular treatments and cultivars but rather to have a wide range of peak load values to correlate with pressure flattened area after storage. There is a correlation ($R^2=0.3895$) when the peak loads were compared to the resulting pressure flattened area after three months' storage in the ventilated containers,

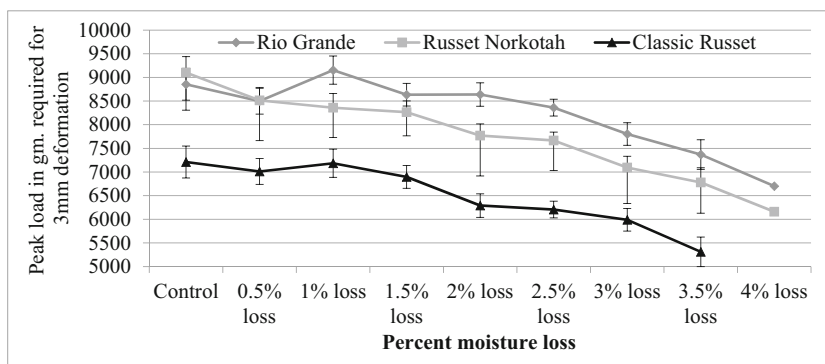
The results in Fig. 5a, demonstrate that, as a group, the samples with lower at-harvest peak loads produced approximately 50% more (9.85 cm^2 vs. 15 cm^2) pressure flattened area per tuber after 3 months of storage. When analyzed by quartile (Fig. 5b), the samples with lowest at-harvest peak loads produced approximately twice as much pressure flattened area per tuber after 3 months of storage compared to the fields in the highest quartile (8.33 cm^2 vs. 17.01 cm^2). There was a significant increase in pressure flattened area per tuber between the upper half of samples when organized by peak load and the bottom half of samples (Fig. 5b). The

Fig. 2 Change in at harvest peak load required for 3 mm tuber surface deformation as tubers lost moisture following harvest from moist soil (2011 data). Analysis using two-way ANOVA with interaction. The factors were Moisture (0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4) and Variety (Classic (CL), Rio Grande Russet (RG), and Russet Norkotah (NK)). The error bars represent the least significant difference at $\alpha = 0.05$



Type 3 Analysis of effects of cultivar, moisture loss, and their interactions				
Effect	Num DF	Den DF	F Value	Pr>F
Moisture	7	439	21.15	<.0001
Variety	2	439	32.44	<.0001
Moisture*Variety	14	439	1.52	0.0995

Fig. 3 Change in at harvest peak load required for 3 mm tuber surface deformation as tubers lost moisture following harvest from moist soil (2012 data). Analysis using two-way ANOVA with interaction. The factors were Moisture (0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4) and Variety (Classic (CL), Rio Grande Russet (RG), and Russet Norkotah (NK)). The error bars represent the least significant difference at $\alpha = 0.05$



Type 3 Analysis of effects of cultivar, moisture loss, and interactions				
Effect	Num DF	Den DF	F Value	Pr > F
Moisture	7	663	29.62	<.0001
Variety	2	663	199.59	<.0001
Moisture*Variety	14	663	1.51	0.1022

pressure flattened area per tuber was 19.06 cm² for the samples with higher peak load values at-harvest and 31.8 cm² for the samples with lower peak load values. The results for the 6-month duration samples also indicated significant differences in pressure flattened area per tuber when different quartiles of the samples were

compared. While there was no difference in pressure flattened area between the upper two quartiles, the upper two quartiles did produce significantly less pressure flattening after 6 months of storage compared to the lower two quartiles. There was also a statistically significant difference in pressure flattened area per tuber between the

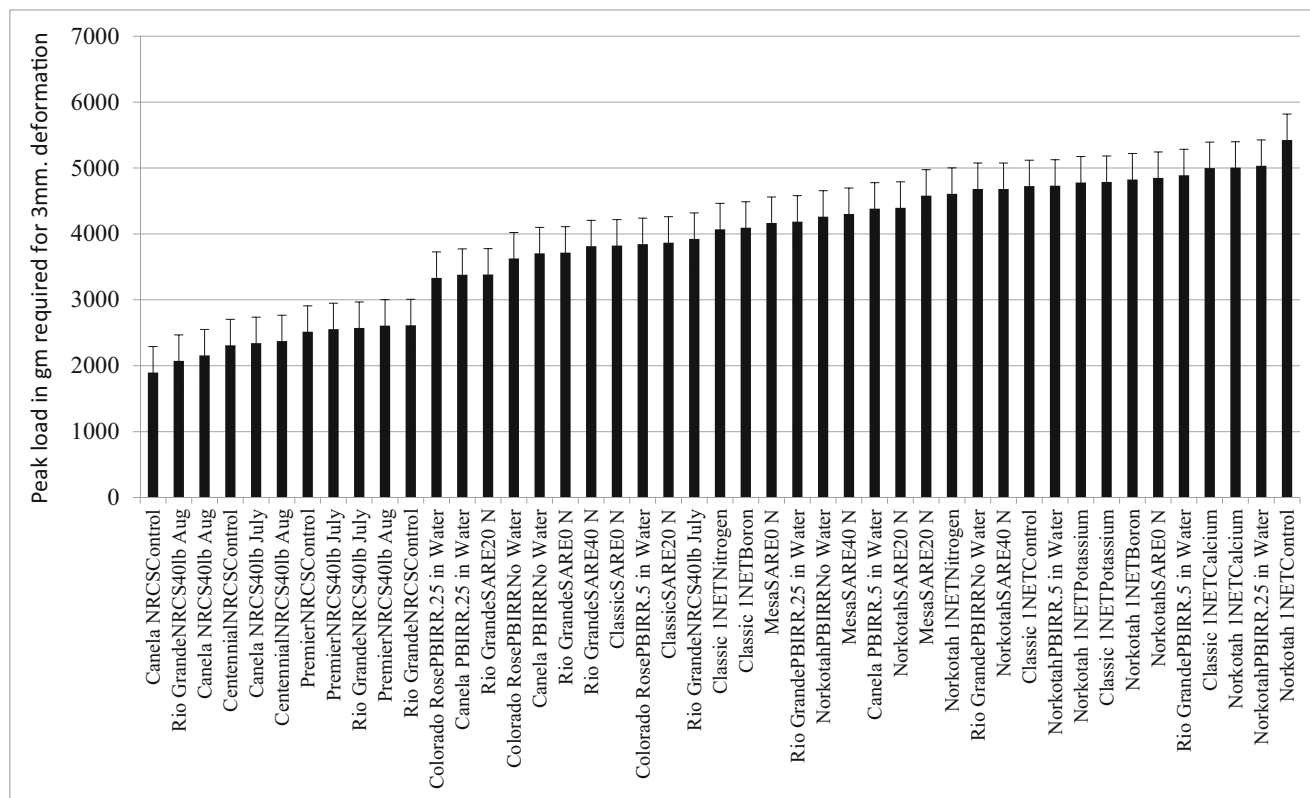
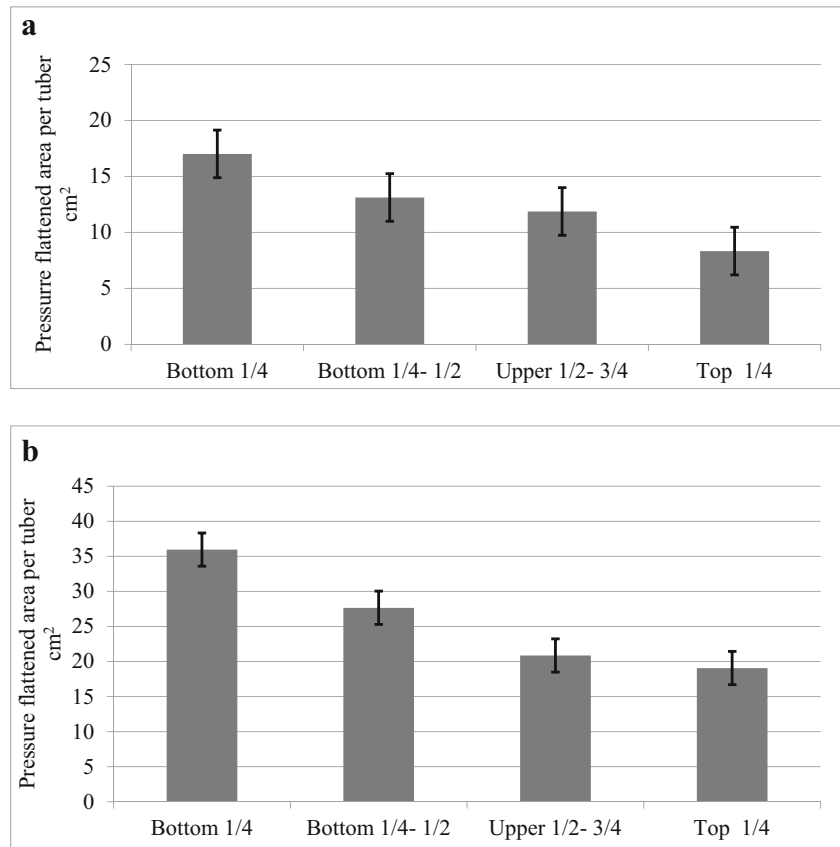


Fig. 4 Comparison of at-harvest peak loads required to cause 3 mm surface deformation across treatments and cultivars from 2011 field research trials. The error bars represent the least significant difference at $\alpha = 0.05$

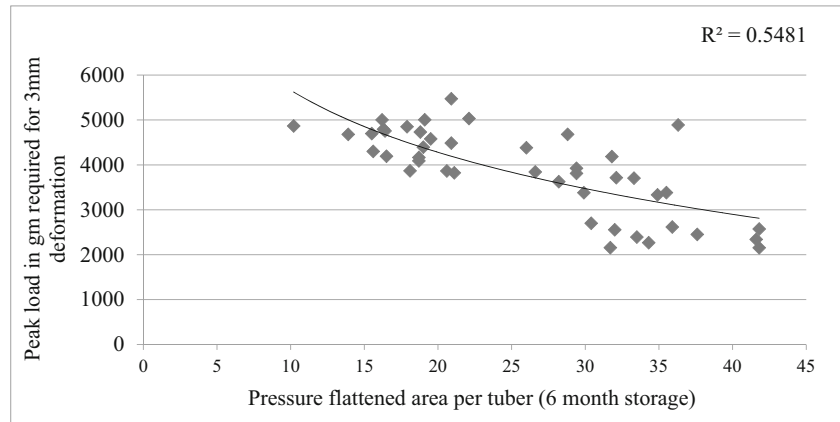
Fig. 5 Comparison of averaged pressure flattened area per tuber (cm²) after 3 months (a) and 6 months (b) storage duration for 2011 field experiments. “Bottom 1/4” is the average of samples that were in the lower 25% of values when arranged in order of increasing peak load required for 3 mm. surface deformation at harvest. “Bottom 1/4–1/2” is the average of samples that were in the lower 25% to 50% of values when arranged in order of increasing peak load required for 3 mm. surface deformation at harvest. “Upper 1/2–3/4” is the average of samples that were in the upper 50%–75% of values when arranged in order of increasing peak load required for 3 mm. surface deformation at harvest. “Top 1/4” is the average of samples in the upper 25% of values when arranged in order of increasing peak load required for 3 mm surface deformation at harvest. The error bars represent the least significant difference at $\alpha = 0.05$



bottom two quartiles, with the lowest quartile producing more flattened area (35.95 cm²) than the next lowest quartile (27.65 cm²).

The at-harvest peak loads for the 2011 samples were also compared to the pressure flattened area per tuber after 6 months of storage duration (Fig. 6). The results indicate a

Fig. 6 Correlation of at harvest peak load required for 3 mm surface deformation with the pressure flattened area per tuber (cm²) after 6-month storage duration. The R-squared value for the correlation trend line is in the upper right corner of the figure. Pearson correlation between texture and bruise area in Cm²/tuber was calculated



Pearson Correlation Coefficients, N = 44, Prob> r under H0: Rho=0		
	Texture	Cm ² /tuber
Texture	1.00000	-0.76843
Texture		<.0001
Cm ² /tuber	-0.76843	1.00000
Cm ² /tuber	<.0001	

correlation ($R^2=0.5481$) between at-harvest peak load and pressure flattening development after 6 months of storage. A similar analysis of pressure flattening development compared at-harvest peak loads was conducted in 2012–2013 involving changes to bulk storage pile height. The correlation for the at-harvest peak loads of samples of 15 cultivars with the resulting pressure flattened areas are presented in Fig. 7. There was also a correlation ($R^2=0.592$) across cultivars between the at-harvest peak load required for 3 mm. surface deformation and the pressure flattened area per tuber after 3 months of storage in a simulated 3.1 m. bulk potato pile. When the different cultivars were segregated into two groups based on increasing peak load values at harvest, there is a statistically significant increase in pressure flattened area per tuber for the cultivars with lower peak loads. This difference occurred regardless of simulated pile height for tubers kept in storage for 3 months (Fig. 8).

Cultivar Susceptibility Results

When the peak load required for 3 mm surface deformation was evaluated for the different cultivars in 2011, Asterix, Russet Norkotah, and Satina all were significantly higher than Innovator or Yukon Gold (Fig. 9a). Similarly, after 6 months of storage duration in the ventilated container system, Yukon Gold and Innovator produced significantly more pressure flattening per tuber in 2011 (Fig. 9b). The pressure flattened area was more than double for Innovator relative to Asterix, Russet Norkotah, and Satina cultivars.

A similar trend was observed when texture analysis and pressure flattening measurements were conducted in 2012. The peak loads required for 3 mm. deformation was significantly higher for Russet Norkotah, Satina and Asterix compared to Innovator and Yukon Gold (Fig. 10a). Data obtained after 3 months of storage from the 2012 storage season indicates a trend towards increased pressure flattened area for Innovator, although there were no observable differences between Yukon Gold and Russet Norkotah or Asterix (Fig. 10b), Satina produced the least pressure flattened area per tuber,

significantly less than Innovator. It must be noted though that the amount of pressure flattening was fairly low because the storage duration was only 3 months.

Conclusion and Discussion

When accounting for potential environmental and climate control differences between storage areas, it was evident that some fields and or cultivars were more likely to develop pressure flattening earlier in the storage season than others. If a predictive test could be developed that could identify the potatoes that were more likely to develop pressure flattening first, it would help improve returns for growers and shippers.

At-Harvest Tests to Measure Tuber Moisture Loss / Turgidity

Peak load measured by the texture analyzer appeared to respond well to both decreases in tuber moisture content, as well as corresponding well with cultivar differences based on the data collected for two years (Figs. 2 and 3). Further tests on a range of cultivars from several fields with different field management treatments also identified differences in peak loads (Fig. 4). The goal of this particular comparison was not to examine specific cultivar or treatment differences, but to test a very wide range of samples so that we could determine whether penetrometer testing would provide a range of values that could be compared with pressure flattening after storage. At harvest, test results are useful for the growers to know which harvested fields and cultivars need to be moved to market to avoid storage losses due to pressure flattening (Fig. 5a, b). The figures show that different fields and varieties in the lower half or quartiles of peak load results had more pressure flattening when removed from storage. So, if a grower of multiple fields and varieties had samples taken at or near harvest and put emphasis on shipping lower peak load potato lots first, economic losses would be reduced.

Fig. 7 Correlation of 3-month storage duration pressure flattening (cm^2) for an equivalent 3.1 m. high pile with at-loading peak load for 3 mm surface deformation

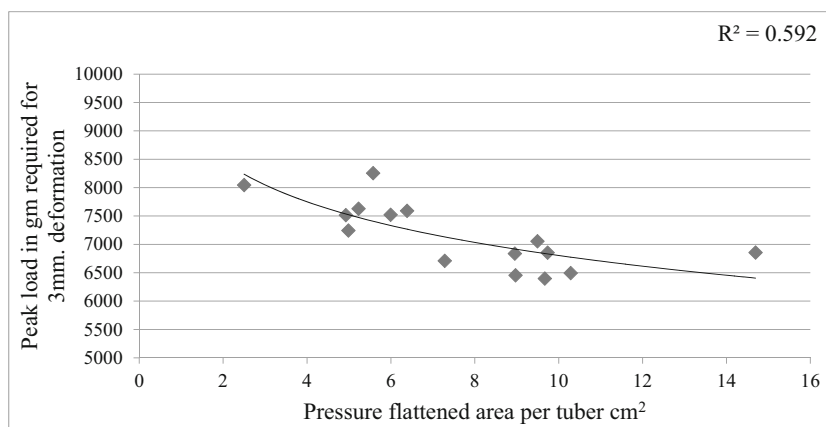
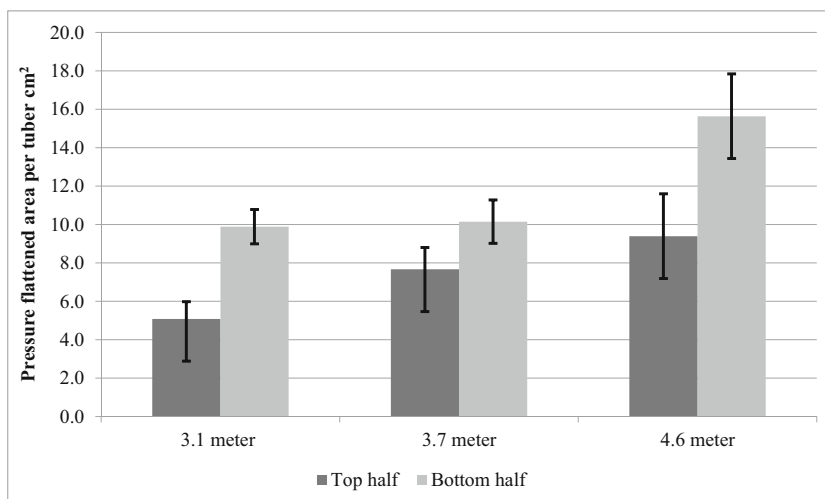


Fig. 8 Comparison of averaged pressure flattened area per tuber (cm²) by pile height. “Bottom half” treatment is the average of samples that were in the lower half of values when arranged in order of increasing peak load required for 3 mm. deformation at harvest. “Top half” treatment is the average of samples in the upper half of values when arranged in order of increasing peak load required for 3 mm deformation at harvest. The error bars represent the least significant difference at $\alpha = 0.05$



Earlier research has suggested that potatoes with lower specific gravity may be more prone to pressure flattening development; (Thornton and Bohl 1998). It should be noted that there can be different reasons for a tuber having higher specific gravity. Higher specific gravity can be a reflection of physiological maturity at harvest or could merely reflect that the tuber is dehydrated, resulting in a higher percentage of solids. At-harvest moisture loss increased the susceptibility to pressure flattening for some cultivars more than others (Castleberry

and Jayanty 2012). The relationship between tuber moisture loss and mechanical properties are well discussed earlier (Castleberry and Jayanty 2012). Pressure flattening is correlated to shrinkage which also causes weight loss in the long-term potato storage. The amount of tuber dehydration, as well as tuber anatomical features, have an effect on tuber mechanical properties (Bajema et al. 1998; Konstankiewicz and Zdunek 2001; Zdunek and Umeda 2005). Another reason for differences in cultivar susceptibility are the differences in pectic

Fig. 9 Peak load required for 3 mm. surface deformation for samples from different cultivars in 2011, after 1 month of storage duration (a), pressure flattened area per tuber (cm²) after 6 months of storage (b). The error bars represent the least significant difference at $\alpha = 0.05$

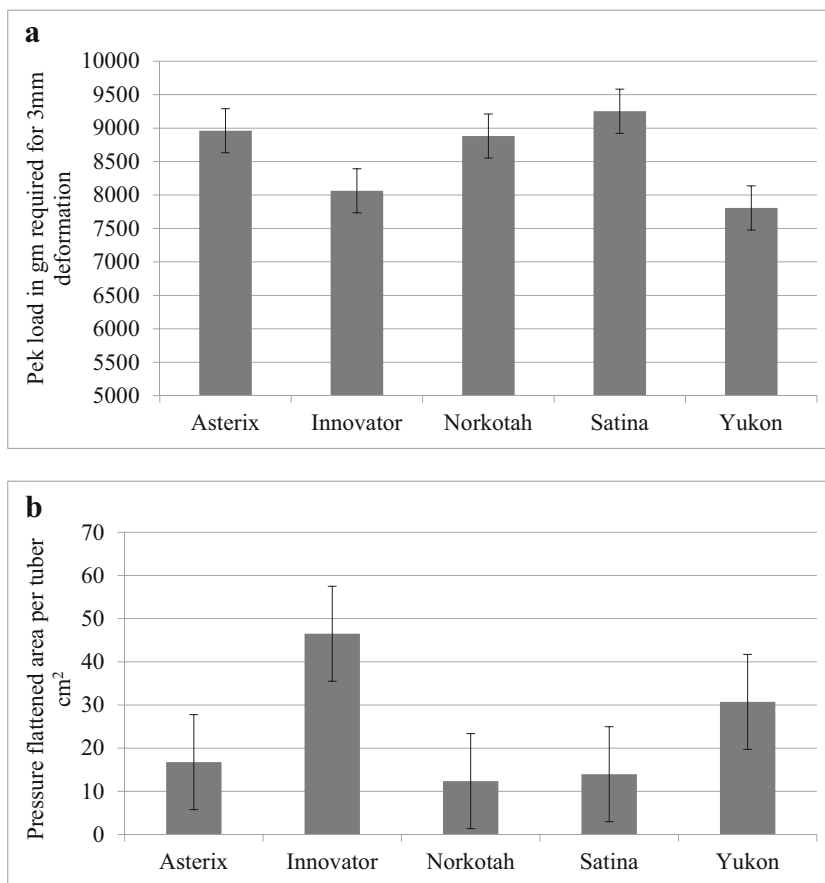
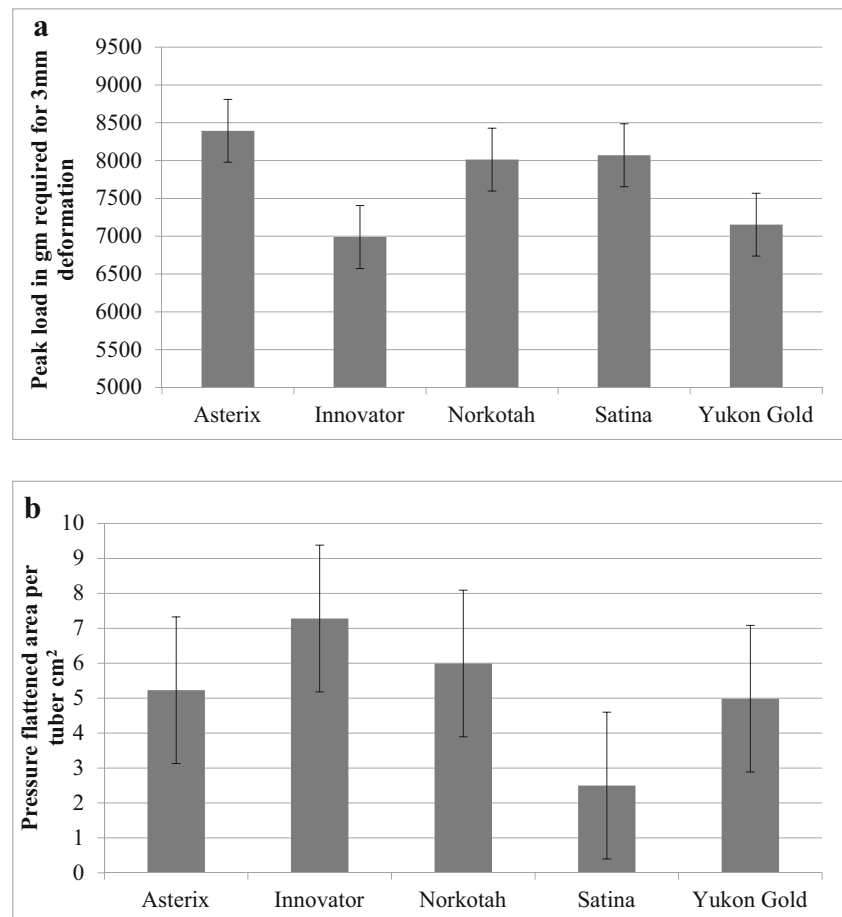


Fig. 10 Peak load required for 3 mm. surface deformation for samples from different cultivars in 2012, after 1 month of storage duration (a), pressure flattened area per tuber (cm²) after 3 months of storage (b). The error bars represent the least significant difference at $\alpha = 0.05$



polymer concentration responsible for cellular adhesion, which provides structural integrity to the tissue (Jarvis et al. 2003). Cell walls comprise the basic structural elements responsible for structural integrity of the tissue. As plant tissue is subjected to pressure during storage, cell wall and tissue resistance to pressure may be due to “reinforcement zones” in which pectic polymer concentration increases cell adhesion (Jarvis et al. 2003), which may have an effect on pressure flattening development.

Development of at-Harvest and Early Storage Season Tests to Predict Relative Severity of Pressure Flattening

Results from preliminary tests applied at harvest (oven moisture loss, whole tuber rehydration, blackspot bruise incidence, specific gravity, relative water content, and resistance to 3 mm. surface deformation) varied between the different cultivars and fields. When data from these at-harvest tests are correlated with the amount of pressure flattening observed after a common duration of storage, the strongest correlations were from measuring peak load required for deformation (Castleberry 2013). At-harvest measurement of the peak load required to deform the surface of the tubers provided correlations with pressure flattened area after storage (Figs. 6 and 7).

The height of the bulk stored potato pile is another important factor in the development of pressure flattening, although pile height can vary among different growers. Our results show that the peak load results were predictive of differences in pressure flattening even when samples were stored at different pile heights (Fig. 8). Growers may also be able to use at-harvest penetrometer testing to adjust pile height for a new cultivar or a cultivar for which a grower is not aware of its pressure flattening susceptibility.

The differences in pressure flattening development between cultivars are significant (Figs. 9 and 10). The data strongly suggests that some cultivars can be stored for much longer durations than others before pressure flattening becomes severe. As discussed in our previous publication (Castleberry and Jayanty 2012), there may be physiological and anatomical features that affect pressure flattening susceptibility, including those responsible for blackspot bruise susceptibility among cultivars (Thornton and Bohl 1998; Corsini et al. 1999). Tuber anatomical features such as cell size, cell wall thickness, and skin thickness may also contribute to the mechanical properties of the tissue (Konstankiewicz and Zdunek 2001; Zdunek and Umeda 2005). Cell size can play an important role in pressure flattening susceptibility. Higher resistance to mechanical stress was also found in smaller-sized cells, but these cells may be

less resistant to micro-damage (Konstankiewicz and Zdunek 2001; Zdunek and Umeda 2005). Changing from more susceptible cultivars to less susceptible cultivars appears to have as great or even greater promise in reducing pressure flattening than any single one of the treatment methodologies that were evaluated by this research program (Castleberry 2013). Therefore, identification of relative susceptibility to pressure flattening among cultivars could be of great benefit to the growers who store potatoes. Determination of which cultivars are more and less susceptible would likely require multiple years of evaluation at multiple durations of storage. Multi-year evaluation can ensure that differences in pressure flattening susceptibility are based on true cultivar differences rather than immaturity of tubers from a cultivar due to non-optimal agronomic management or unusual growing conditions. Development of pressure flattening “cultivar trials” could enable identification of near release cultivars and existing commercial cultivars that can be stored profitably for longer durations or at increased pile heights.

Based on the differences in the resulting pressure flattening between the groups of fields and cultivars arranged based on peak load values, it appears that use of texture analysis at-harvest will identify the majority of potatoes that are likely to pressure flatten earlier in the storage season. This discovery represents significant progress in providing guidance to growers that can determine an optimal order of shipping across multiple fields and cultivars.

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