DISSERTATION

DEVELOPMENT OF METHODS TO ESTIMATE OR REDUCE PRESSURE FLATTENING OF POTATOES DURING STORAGE

Submitted by

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In partial fulfillment of the requirements

For the Degree of Doctor of Philosophy

Colorado State University

Fort Collins, Colorado

Spring 2013

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ABSTRACT

DEVELOPMENT OF METHODS TO ESTIMATE OR REDUCE PRESSURE FLATTENING OF POTATOES DURING STORAGE

The physiological disorder referred to as pressure flattening is a cause of significant economic losses in storage of Irish potatoes (*Solanum tuberosum* L.) intended for use as fresh market or "table stock". As the flattened area on each tuber becomes larger in diameter or becomes more depressed, the USDA quality grade, and therefore market value of the potatoes, is reduced. 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. Pressure flattening occurs as potatoes are stored in bulk storage bins and are exposed to pressure over time from the weight of other potatoes above them in the pile of potatoes. The force/pressure/weight of the potatoes is transferred to the individual potato at the points of contact with adjacent potatoes or with the storage structure itself (walls, ducting and floor). These contact points become the flattened, depressed areas that cause the reduction in quality. The physical deformation of the tubers due to these pressures comes from the crushing of the outer layers of periderm and underlying cells. The height of the pile in which the potatoes are stored and the duration that they are stored therefore become critical to determining the accumulated pressure to which the tubers are exposed. However, due to the monetary costs involved in building additional climate controlled storages and the irregularity of the timing of purchase and movement of stored potatoes, it is difficult to address pressure flattening by reducing storage duration and pile height. The development of pressure flattening is also a result of dehydration of the tubers that occurs during harvest and storage. This dehydration can be the result of contact with dry soil or soil air prior to harvest, moisture loss during harvest and shipping to storage, moisture loss from wounded or damaged tissue, moisture loss due to vapor pressure deficit, and moisture loss through a poorly suberized, immature periderm during the first

days to weeks of storage, and moisture loss due to respiration and dehydration by lower humidity ventilation air throughout the duration of storage. A final factor in the development of pressure flattening are cultivar specific traits which have yet to be fully identified but most likely relate to cell wall structure, spatial arrangement of periderm cells, and possibly concentration of starch and/or of amyloplasts in the tissue. This doctoral research program was undertaken to 1) develop a controlled method to induce pressure flattening that can be used to evaluate the impact of factors related to pressure flattening 2) develop a method for predicting which lots of potatoes, once stored, are more likely to pressure flatten early or severely so that they can be preferentially shipped earlier than other stored potato lots to avoid rapid declines in tuber quality, and 3) identify methods that can be used during the growing season or after harvest that can either delay/reduce pressure flattening by reducing or delaying factors associated with moisture loss or cultivar susceptibility.

This doctoral dissertation is based on three years of study and experimentation focused on understanding causes of pressure flattening and identifying methods to reduce the negative economic impacts of the disorder on the fresh market potato industry. Results from the accumulated research confirm the importance of moisture loss, storage duration, pile height, and cultivar susceptibility in the development of pressure flattening. A controlled system for inducing pressure flattening while maintaining conditions nearly identical to bulk potato storage was successfully developed. The development of this system has allowed for a controlled evaluation of different cultivars and treatments for their rate and severity of pressure flattening development. Experimentation was conducted to determine if it was possible to identify at-harvest or early in the storage season which potato lots within and among cultivars were likely to pressure flatten earlier or more severely. Several different at-harvest methods for testing relative dehydration and other properties thought to be related to increased pressure flattening development were evaluated and compared to subsequent pressure flattening. The use of an instrumented penetrometer or texture analyzer to measure peak load required for periderm deformation at harvest appears to correctly anticipate the majority of fields from which tubers are more likely to have severe pressure flattening at 6 months storage duration compared to those fields from which tuber would develop less pressure flattening. Potato lots, regardless of cultivar, that required higher amounts of pressure to deform at-harvest produced less pressure flattening after months of storage. As a result of this finding, one major Colorado potato producer is already using at-harvest texture analysis to determine order of shipping. This testing method is likely to be developed into a service to assist other potato producers in making decisions about which storage bins should be shipped early in the storage season. Year to year evaluation of pressure flattening of multiple cultivars supports the conclusion that there are cultivars that consistently pressure flatten more severely than other cultivars that are of a similar type (russet, red skinned, yellow skinned). Applications of nitrogen, calcium, potassium, and boron during the late growing season were evaluated to determine if there was an effect on the rate of pressure flattening development. Although applications of nitrogen late in the growing season can result in an increase in susceptibility to physical damage and may delay suberization and periderm maturation, the results from this research were not clear on the effects of late nitrogen on pressure flattening. The majority of significant increases in pressure flattened area per tuber occurred when additional late nitrogen was applied, but at times there was more pressure flattening at the intermediate 22.5 kg per hectare application rate, compared to both the control and 45 kg. per hectare additional application rate. There were no significant differences in pressure flattening development for potatoes that were grown with additional late growing season applied calcium, boron, or potassium applied either individually or in combination The effect of irrigating after vine kill to avoid in-field dehydration was evaluated over two years. Results indicated that the pressure flattening was reduced if post vine kill soil water capacity was maintained between 60-75% depending on the cultivar. Pressure flattened area per tuber increased for some cultivars when irrigation treatments resulted in soil water content above 75% and increased for other cultivars when soil water content fell below 65%.

The factors of pile pressure, moisture loss, and storage duration are likely to cause significant pressure flattening, even with the optimal management during extended storage durations beyond 5to 6 months. However, it is the conclusion of this research that potato growers and shippers can significantly reduce their economic losses from pressure flattening, especially at 3 to 6 month storage durations by adopting a combination of practices that are feasible for their individual production system. Identification and planting of cultivars that are more resistant to rapid development of pressure flattening and/or are less likely to develop discoloration of tissue below flattened areas can greatly reduce economic losses. Crop management that minimizes late growing season nitrogen fertilization and maintains adequate soil moisture to promote skin maturation and avoid dehydration can improve physical maturity and reduce the rate of pressure flattening in storage. Management of the crop that reduces physical damage and skinning at harvest and minimizes moisture loss between vine kill and the first weeks of storage can also significantly delay pressure flattening development for at least some cultivars. Reducing the height of the bulk piles in which potatoes are stored appears to reduce early development of pressure flattening and may be economically feasible, especially for higher value specialty potato crops such as red potatoes. Lastly, use of carefully implemented at-harvest texture analysis of tubers from different fields and cultivars as the potatoes are loaded into storage, could allow growers to identify and ship lots of potatoes that are more susceptible before they develop significant pressure flattening.

ACKNOWLEDGEMENTS

It should be noted that this research program would not have been possible to complete without the support and understanding provided by my wife Elita, my daughters Marcelina and Cecelia, and my parents Henry and Silvia Castleberry. I would also like to thank my "potato" mentor Dr. Robert Thornton and my doctoral advisor Dr. Sastry Jayanty for their help in editing this dissertation and years of guidance in both scientific endeavors as well as my understanding of the proper role of research as providing a benefit to others.

I also wish to thank my graduate committee, Dr. David Holm, Dr. Ken Barbarick, and Dr. Steven Wallner.

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GENERAL INTRODUCTION AND LITERATURE REVIEW.

Physiology and Causes of Pressure Flattening:

The physiological disorder pressure flattening is a major cause of economic losses in bin stored potato crops. 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 (Rowe, 1993). Pressure flattening occurs as potatoes are stored in bulk storage bins and are exposed to pressure over time from the weight of other potatoes in the bin. Long-term storage of up to 12 months raw product is necessary to provide a year round supply of potatoes to the market.

Pressure flattening occurs as the tuber surface becomes depressed or flattened due to constant contact from a portion of an adjacent tuber (Figure 1). This area of contact also receives the force exerted by the adjacent tuber as a result of the weight of tubers above it in the pile. The downward force or pile pressure is approximated as 672 kg./m^3 of pile above the potato (Muthukumarappan at al., 1994). Potato growers and shippers often store russet potatoes in bulk piles up to 6 meters in height. In the San Luis Valley of Colorado, specialty potato cultivars such as fresh market red and yellow potatoes are also stored in pile heights up to 6 meters. The area of greatest pressure flattening is approximately 1-2 meters from the floor due to this pressure of pile potatoes above and the distribution of ventilation air. This also corresponds to the area of maximum lateral pressure from the pile (Matson and Helleckson, 1983).

Figure 1. Photograph of Canela Russet tubers with pressure flattening

Tuber moisture loss is regarded as an important factor in increasing the susceptibility of tissue to forming depressions and the extent of bruise in response to force (Kunkel and Gardner 1965; Hughes 1980; Lin and Pitt 1986; Muthukumarappan, et al. 1994; Konstankiewicz and Zdunek 2001; Olsen and Oberg 2003). As tuber moisture loss increases, cellular turgor decreases resulting in reduced mechanical resistance of the tissues. These tissues are more prone to changes in cell shapes, cell wall cracking, debonding of the cells, and leakage of intracellular liquids through the cell walls (Konstankiewicz and Zdunek 2001). Reduced turgidity of the outer layers of tissue can cause increased susceptibility to pressure flattening although excessive turgidity of tissue may also reduce resistance to deformation due to increased cell wall fracturing under pressure (Zdunek and Bednarczyk 2005). Dehydration and water loss from potato tubers occurs between vine kill and the final use by a consumer or processor. The tubers lose moisture through the outer most layers of periderm, due to evaporative loss and respiration. Once the vines of a potato plant senesce or are chemically or mechanically vine killed, senescence of the underground stems and stolons also occurs. Tuber moisture content is then no longer contingent on water provided through the plants root system. After vine kill the tubers may gain or lose moisture depending on the availability of water in the soil, or water tension, and also as a factor of soil air humidity. If there is too much free moisture in the soil, tubers may become more susceptible to disease or may become highly turgid or "crisp" which may cause the ends to shatter if damaged during harvest, a disorder known as shatter bruise. Dry soil prior to harvest can result in flaccid, dehydrated tubers at the time of harvest. These tubers may be especially sensitive to pressure or may respire more as a result of moisture stress. Additionally, these tubers may be more susceptible to blackspot bruise damage during harvest (Thornton and Timm, 1990).Tuber skin maturation and suberization of the periderm that takes place after vine kill can reduce the susceptibility of the periderm to lose or gain moisture.

Rapid loss of moisture from the tubers can take place at harvest and during the first weeks of bulk storage. Moisture loss at harvest appears to be greatest in potatoes that are not fully matured or have poorly set skin (Thornton and Bohl 1998). Moisture loss during harvest results from the removal of the tubers from the soil as they are maneuvered through the harvester and loaded onto trucks for transport to storage. Harvesting in low relative humidity during the warmer part of the day, followed by transport in open air vehicles can increase dehydration of the tubers. The difference in temperature and humidity between the tuber and the environment during harvest and storage is the vapor pressure deficit (Olsen and Odberg 2003). The greater the vapor pressure deficit, the more moisture can be lost from the tuber during harvest and storage. Transpiration accounts for 90% of tuber weight loss and is mostly due to diffusion of water vapor through the skin to the surrounding air (Lutman, 1934). Research has also determined that the amount of moisture that is lost through the periderm can increase up to 60 fold if a tuber is immature or damaged (Kleinschmidt and Thornton, 1991). Skinning and cutting of tubers can increase moisture loss from the tubers up to 1000 times that of a non-damaged, well suberized tuber (Olsen and Odberg, 2003). Within the pile of stored potatoes, tubers near the bottom will dehydrate the most due to proximity to the inflow of cool ventilation air. Tuber weight loss after harvest is the combination of transpiration and respiration processes. The estimated weight loss due to transpiration is 5 to 10 % of total tuber weight during 8 to 9 months of storage. Mature potatoes respire at a rate of 5 ml O_2/kg/h (Rastovski et al, 1981). This corresponds to approximately 1.5% in weight loss in 8-10 months of storage. Potatoes immediately after harvest lose water three times faster than they do after one month of storage. Shrinkage loss is greater during the early part of the storage season due to factors such as higher tuber respiration rates, higher storage temperatures, and higher transpiration. During the preliminary period of storage, tubers wound heal by developing a suberized layer, which retards water evaporation during the subsequent storage duration. Tuber moisture loss begins to increase again as tuber dormancy (quiescence), a naturally occurring duration of reduced respiration, ends and tubers in storage begin to ”wake up”. Sprout formation during storage, which often begins at the end of the period of physiological rest, will cause additional moisture loss. As a result, effective sprout control is necessary to minimize potato dehydration and therefore pressure flattening, during long durations of storage. The pressure flattened areas are made up mostly of crushed periderm (Lulai et al. 1996) and can become a source of moisture loss after removal from storage because they are more susceptible to evaporation from damaged cells (Lulai et al. 1996).

Economic Impacts of Pressure flattening

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 generally more severe for potatoes intended for the fresh potato sales, however pressure flattening accompanied by discoloration of the underlying tissue is a major concern for chipping and processing users as well. The severity of pressure flattening losses is often not apparent until the potatoes are removed from storage.

The 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 being downgraded to USDA No. 2 or lower. This often reduces returns to potato grower/shippers by 40% or more. By late spring some lots of potatoes may have as much as 70-80% of tubers with pressure flattening (Eric Allen, personal communication). This can result in half a bin of potatoes being thrown away in order to meet a grade standard desired by a buyer. In addition to the sunken depressed area itself causing a reduction of quality grade, the development of discoloration below the surface can reduce quality grade as well and may not develop until up to 5 days after the potatoes are first unloaded. This is thought to be due to limited oxygen availability to the damaged area until the potatoes are removed. In some instances, a shipment of potatoes with moderate pressure flattening is inspected, certified, and shipped out of bulk storage as a higher value US No.1 shipment and a few days later packed into final consumer packaging, and sold to retail markets. It is not until the fourth or fifth day when the potatoes reach the retail outlet that the pressure flattening has resulted in discoloration and/ or additional breakdown which results in the quality being downgraded and the shipment rejected by the purchaser. This delay in being able to determine the final extent of pressure bruise damage can result in an additional 20-30% loss due to the costs associated with shipping and packing that took place after the initial inspection.

Current Techniques for Reduction of Pressure Flattening

Recommendations have been developed to minimize moisture loss and damage at harvest that may contribute to pressure flattening (Thornton and Bohl, 1998) These recommendations are based on minimizing physical damage to tubers at harvest and providing optimum temperatures and humidity for the crop during bin loading to minimize stress and moisture loss (Thornton and Bohl 1998, Voss et al. Shetty, Smittle et al. 1974). Some research indicates that an immature crop may lose10-60 times more moisture than a crop that is allowed to senesce and set skin (Kleinschmidt and Thornton, 1991) Pressure flattening can also result from moisture loss during the storage season. This moisture loss can be reduced by maintaining above 90% relative humidity in the air supplied for tuber ventilation and also by maintaining tuber quiescence through sprout inhibiting treatments (Caldiz et al. 2001 and Pavlista, 2005). However, even storage operations that utilize these recommendations may have severe economic losses due to pressure flattening. It has also been suggested that there may be a connection between low specific gravity and increased pressure flattening, although it is unclear if this is a reflection of an immature crop rather than an actual effect of solids content (Thornton and Bohl, 1998).

Below is a list of storage management suggestions to reduce the potential of pressure bruise development (Adapted from Olsen and Oberg, 2003).

1. Apply water to the open areas storage floors before and during bin loading to increase relative humidity.
2. Use tarpaulins over the potatoes if an open top vehicle will be used to transport the potatoes from field to storage.
3. Do not pile potatoes higher than 5 meters during bin loading. Further reduction in pile height is recommended if storage space is not limiting.
4. Apply humidified ventilation air to the storage bin during loading.
5. Humidity above 95% is optimal for the duration of storage. When possible it is better to use outside air rather than having the ventilation system re-circulate air.
6. Measure the tuber pulp temperatures as loads of potatoes arrive from the harvesting operation. Do not have the environmental control system set point more than a few degrees below the coolest pulp temperature during the day.
7. Allow at least 2 weeks for the crop to suberize after they are loaded into storage. This can be done by maintaining the potatoes at about 10ºC (50ºF). Suberization and wound healing may require longer amounts of time if the crop was damaged at harvest or the crop did not mature in the field.
8. Holding potatoes stored for the fresh market at low temperatures 4.5-7.2ºC (40-45ºF) will minimize weight loss. Maintain a less than a 1ºC (2ºF) differential between the top and bottom of the pile by applying additional ventilation air if the heat generated by the stored potatoes is not being removed from the upper part of the pile. This recommendation requires the storage operator to take pulp temperatures of tubers near the bottom and top of the pile every few days.

9. Apply sprout inhibitor treatments on schedule to avoid additional moisture loss, depending upon past experience with the cultivar and crop. Frequent observations of the crop in storage will help determine optimal timing of application.

Objectives for the Doctoral Research Program:

This graduate research program was developed to 1) develop a controlled method to induce pressure flattening that can be used to evaluate the impact of factors related to pressure flattening 2) develop a method for predicting which lots of potatoes, once stored, are more likely to pressure flatten early or severely so that they can be shipped before pressure flattening causes significant declines in tuber quality 3) find methods that can either delay or reduce pressure flattening that can be implemented in-season or at-harvest and 4) improve understanding of the causes of early pressure flattening in storage. The experimental research was conducted over three years between 2009 and 2012 and was developed based on practices used and cultivars grown in the San Luis Valley of Colorado.

SECTION 1. DEVELOPMENT OF A RESEARCH METHODOLOGY TO INDUCE AND MEASURE PRESSURE FLATTENING

An important step in developing the pressure bruise research program was to devise a method to create pressure flattening in samples to determine which growing season or postharvest treatments resulted in differences in pressure flattening development. Additionally, samples that would be induced to pressure flatten under controlled conditions would identify which at-harvest measurements could give the best indication of future pressure flattening during storage. The initial methodology for inducing pressure flattening consisted of using replicates of roughly 12 kg. of treatment or control potatoes placed in red 20 kg. mesh onion sacks. During bin loading, the samples were placed in the potato piles of commercial storages near the wall at about 1 m. from the floor (Figure 2). These samples would theoretically be exposed to both high velocities of ventilation as well as the pressure of most of the height of the pile. These samples were evaluated for pressure flattening when the commercial bins were unloaded. However, the inherent problems of this experiment were: 1) that it is difficult to control whether a bin may be unloaded before pressure flattening occurs, 2) whether the surrounding potatoes will have excessive disease that can spread to the research samples, and 3) to prevent tuber breakage or loss of samples when they are pulled from the pile during unloading. In the 2008-2009 storage season, samples intended to determine relative cultivar susceptibility to pressure flattening were placed in 19 separate storage bins at two different storage operations. Of the 19 sets of samples, 15 were in bins that were unloaded by the middle of December, which is often at least a few weeks before significant pressure flattening typically occurs. Two of the remaining sets of samples were in bins that had a high percentage of potatoes developing soft rots and storage diseases, resulting in those samples being decayed and non-usable. The remaining two sample sets were retrieved months apart and provided only marginally useful data.

Development of the Ventilated Container System to Induce Pressure Flattening

It was evident that the success of any research to determine methods to anticipate or reduce pressure flattening of stored potatoes depended on developing a system in which pressure flattening could be induced under conditions similar to those in a bulk storage (Figure 3) while maintaining control over the date that samples are retrieved and minimizing factors such as sample damage due to the spread of disease through a bin. As a result, an alternative method (the crib or ventilated container method) of causing pressure flattening was developed by myself and Dr. Jayanty with input from Kendall Nye, a potato farm and storage manager (Figure 4). Ventilated, plastic bulk produce containers (122 cm X 122 cm X 79 cm HDPE plastic) were used to provide an environment for inducing pressure flattening. A layer of filler potatoes approximately 15 cm. is first placed across the bottom of the container (Figure 4 “D”). Several 2.2 kg. mesh potato bags containing up to 10 tubers from each treatment, randomly selected from the freshly harvested potatoes are labeled were placed on top of these potatoes(Figure 4 “E”) and then more filler potatoes (Figure 4”D”) are added to reach the upper rim of the container. A 107 cm X 107 cm sheet of 2.5 cm thick plywood that has been precut with 20 equally spaced 5 cm diameter holes is placed across the surface of the potatoes in the container, taking care to avoid contact between the plywood and the sides of the container. A concrete block (Figure 4 “C”) is placed at each corner of the plywood sheet plus one in the middle of the sheet. The 1042 l. capacity water tank (Figure 4”A”) is supported and kept level atop the wooden support pallet (Figure 4”B”). The concrete blocks allow for the water tank and pallet to move downward as tubers are compressed without the water tank and its supporting pallet resting directly upon the ventilated plastic container. A length of 46 cm diameter polyethylene plastic greenhouse air exchange tube (Figure 4 “F”) with precut air release holes is connected to a 46 cm circular fan that was placed above the 10 mil plastic sheeting (not shown in the image) between the two rows of elevating concrete blocks (Figure 4 “G”). Plastic sheeting extending past both sides of the concrete blocks is then carefully sealed to the sides of the containers. The plastic sheeting can be secured using duct tape and construction staples, forcing the air supplied from below to move upward through the containers of potatoes. Before the containers were assembled the polyethylene ventilation tube was attached to the fan to check the ventilation air output of the system. An anemometer was used to determine that each hole in the air exchange tube provided air velocity of 28-30 $m^3\ min^{-1}$, which is comparable to that supplied by holes cut in the round metal ventilation tubes used in commercial potato storage cellars.

For the experiments conducted, the potato filled ventilated containers were placed tightly together with the continuous air exchange tube beneath them. In initial testing of the design, a custom fabricated pressure plate was placed in the bottom of the container. The pressure plate provided a means to determine whether the force of the additional weight added was being exerted downward through the potatoes into the area with the samples or merely being distributed into the walls of the container itself. It also provided a means to calculate the approximate commercial storage pile height that corresponds with the force exerted on the samples. The pressure plate showed that this apparatus once full of potatoes and topped with 1040 l. of water in the tank could apply approximately 1225 kg per m^2 of pressure to samples located in the lower portion of the ventilated container. This is approximately equivalent to 2.4 m. of potatoes above the sample bags based on an observed weight of 494 kg of russet potatoes per m^3. This corresponds to pressures near the mid-height of a 5 m high potato pile in a commercial storage cellar.

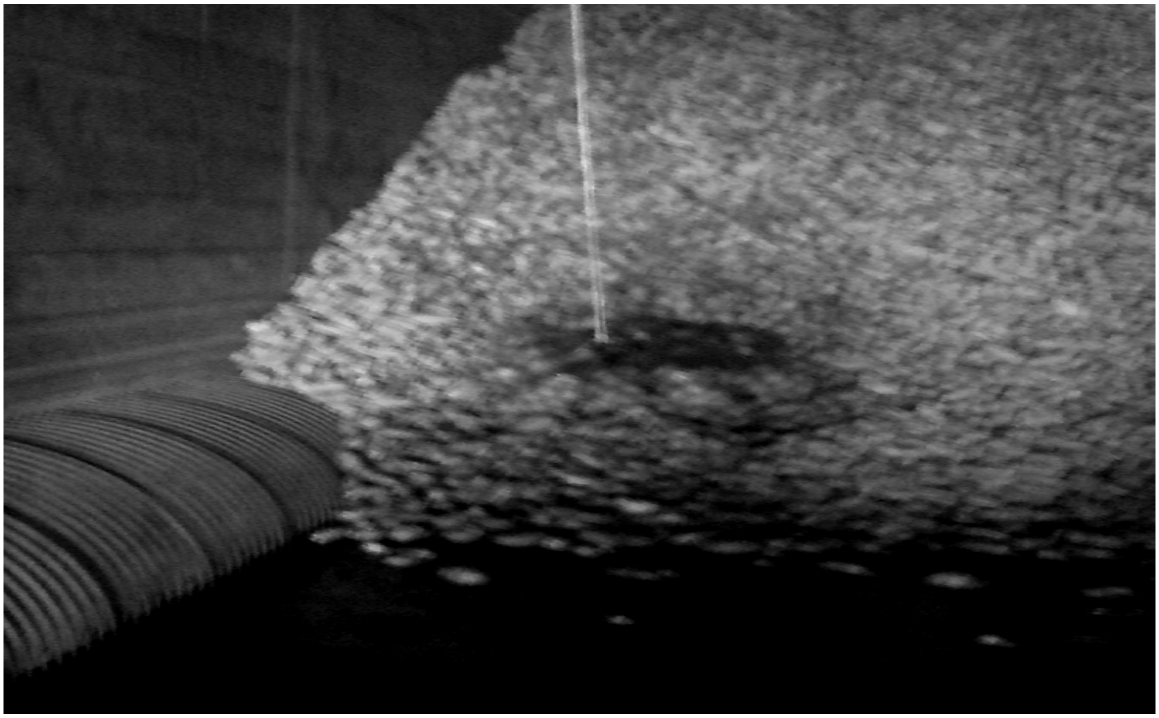

Figure 2. Example of research samples placed in commercial storage pile.

Figure 3. Example of typical bulk storage pile (5 m. pile height) in the San Luis Valley of Colorado

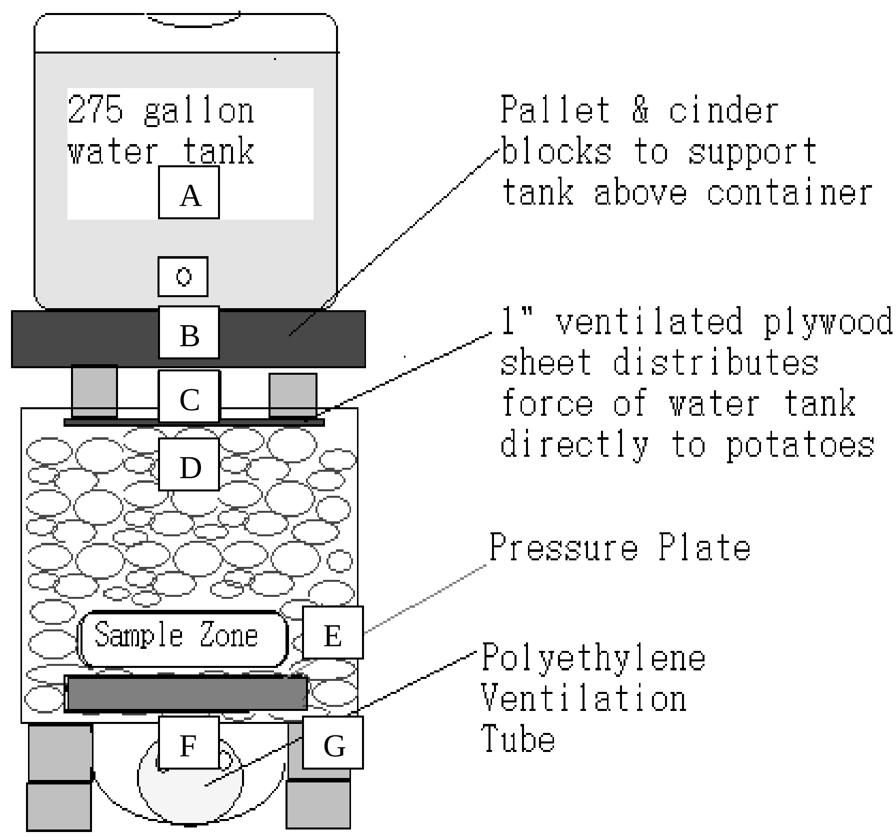

Figure 4. Diagram of the ventilated container design for inducing pressure flattening in storage.

The use of the ventilated container and water tank system successfully induced pressure flattening over the course of several months of storage (Figure 5). The flattening proceeded at a similar rate to what is seen in commercial storages in the same geographical area with pressure flattening developing in December and January (3 months storage duration) and then producing bruise in excess of grade standards in the months of March and April (5-6 months storage duration). The measured and calculated pile pressure of approximately 2.4 m. of pile pressure (800 kg./m. sq.) above the samples was sufficient to produce pressure flattening in the sample zone when the ventilation system was run continuously, rather than using the pile temperature based run times used by commercial storage operators. Potential limitations of the design were that because inflation of the poly-tube regulated the air flow, there is limited opportunity to reduce air flow rate, although power to the fan itself can be controlled through the use of a timer to simulate different run times that are used by commercial storages. In addition, studies may use the amount of water used in the water tank to supply different pressures to simulate different commercial pile heights. This would allow for development of cultivar specific pile height recommendations. The relatively large tuber holding capacity of the ventilated container allowed for sufficient replications of each treatment so that the inherent potential of the design to produce differences based on location within the sample zone were minimized.

The advantages of the ventilated container design for inducing pressure flattening were:

1. The physical mechanism of pressure flattening in the cribs is nearly identical to that of pressure flattening in commercial storage operations.

2. The ventilated container design allows for evaluation of multiple treatments and replications within the same container.

3. The design allows for simulation of different pile heights by adjusting water tank fill levels and for different amounts of ventilation by controlling power to the fan.

4. The additional pressure/ weight provided by the water tank can be added and removed with minimal movement of the potatoes within the ventilated container.

5. The researcher has more control over the date that the samples are retrieved than when using samples placed within a commercial storage pile.

6. There is a reduced likelihood of damage to the samples when they are retrieved as well as reduced influence of storage rot on results with the crib design. In part this is because it is easier to hand select the additional potatoes used to fill in above and below the research samples, discarding any that are damaged or obviously diseased.

Figure 5. Example of pressure flattened tubers retrieved from the ventilated container design.

The limitations of the ventilated container design were:

1. The ventilated containers need to be placed within a storage area that can maintain a desired temperature and relative humidity.
2. The design limits calculated pressure applied to no more than 2.4-2.75 m. of pile pressure above the sample area (with 1040 l. water tank completely filled).
3. There is a potential for effects resulting from the positioning of samples within the sample area but this can be controlled through sufficient replication and randomization of placement within the area of the container.
4. The water tanks used to apply additional weight/pressure can tilt or shift during storage season but they can be drained in place, adjusted, and refilled without any physical movement of the potatoes in the crib.

Evaluation Methodology for Determining Severity of Pressure Flattening:

When samples were removed from the commercial storage of the ventilated container system, each tuber within each sample bag "replicate" was evaluated. For the initial research in 2009 and 2010, samples were graded as scorable (pressure flattening in excess of the area allowed as a US No.1 potato) or not scorable (pressure flattening within the USDA pressure flattening grade standard) (see Table 1 below). After the initial storage season, pressure flattening was evaluated in more detail. Each tuber with pressure flattening had each flattened area measured, numbered, and diameter of each area recorded (Figure 6). This data could be used to compare aggregated pressure flattened areas numerically as well as to determine the approximate USDA quality grade of each tuber in each sample bag. The percentage of tubers in each USDA grade can also allow for differences in pressure flattening to be presented as dollars saved or lost by treatment at different storage intervals. The flattened areas from the samples had the surface skin removed by peeling (approximately 3mm. thickness) 3-5 days after initial removal from the ventilated containers for the 2010-2011 storage season. The tissue beneath the peeled skin was then visually inspected for the occurrence and severity of discoloration under the flattened areas. Very few peeled areas had even mild discoloration and no conclusions could be made based on the data obtained.

Table 1. USDA Tolerances for Pressure Flattened Areas by Grade Standard (converted to metric)

Tuber Diameter	Tuber Weight	No. 1 (aggregate area)	No. 2 (aggregate area)
Potato is:	Potato is:	Not more than:	Not more than:
Less than 5.08 cm.	Less than 113 g.	1.27 cm.	2.54 cm.
5.08 to 6.35 cm.	114 to 170 g.	2.54 cm.	3.81cm.
6.36 to 7.62 cm.	171 to 227 g.	3.18 cm.	4.45 cm.
7.63 to 8.89 cm.	228 to 397 g.	3.81 cm.	4.76 cm.
8.90 to 10.16 cm.	398 to 567 g.	4.45 cm.	5.08cm.
10.17 to 11.43 cm.	568 to 794 g.	5.08 cm.	5.72 cm.
11.44 to 12.7cm.	795 to 1021 g.	5.72 cm.	6.99 cm.
More than 12.7 cm.	More than 1021 g.	6.35 cm.	8.26 cm.

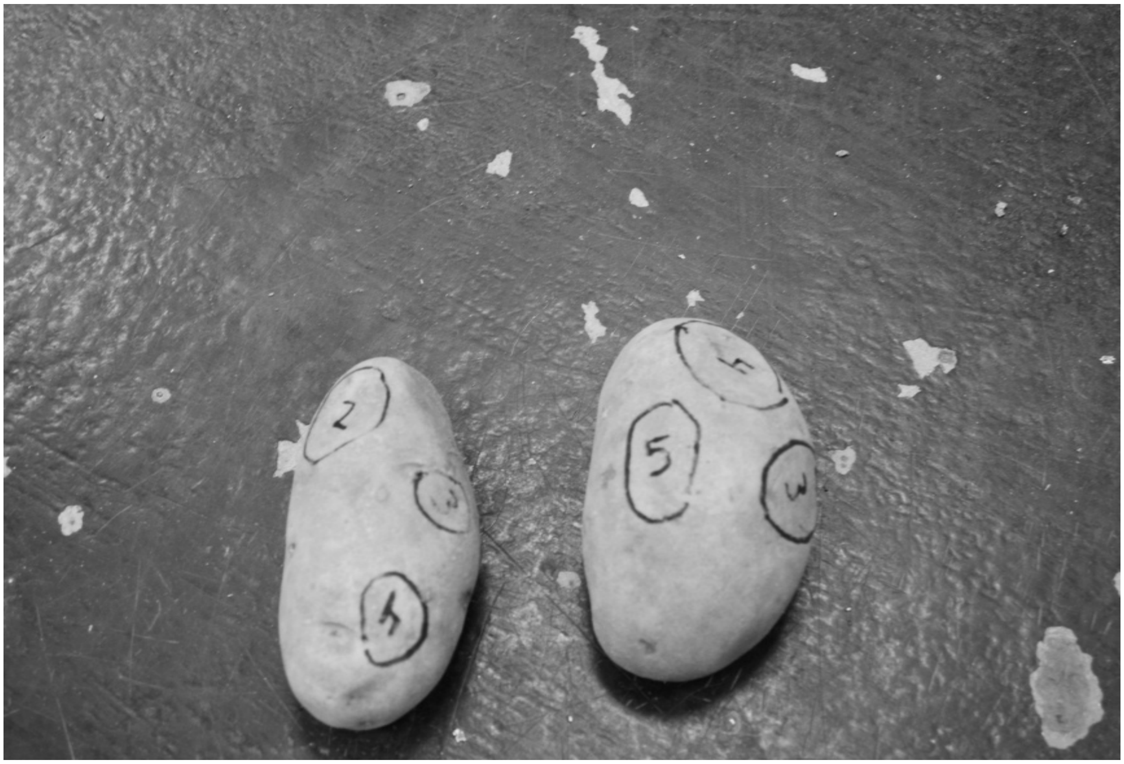

Figure 6. Example of evaluation methodology to determine pressure flattening following storage experiments.

SECTION 2. DEVELOPMENT OF AT-HARVEST AND EARLY STORAGE SEASON TESTS TO PREDICT RELATIVE SEVERITY OF PRESSURE FLATTENING

Introduction to Predictive Tests:

A considerable challenge faced by potato farms and shippers is successful determination an optimal "shipping order". In other words, growers must do their best to 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. It was decided that if an at-harvest or early storage season test could determine which fields or cultivars would pressure flatten first it would help growers determine 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. This should, on average, reduce economic losses due to pressure flattening. An initial step in determining whether to consider an at-harvest testing methodology to predict pressure flattening would be to determine if there is variability in the response of samples, both among and within cultivars with regard to the factor being tested. Secondly, there was a need to be able to correlate data from these at-harvest tests with the amount of pressure flattening observed after a common duration of storage. Our initial testing was done using a mixture of samples from different fields and cultivars. Based on the previous research on maturity differences resulting in moisture loss and therefore, potentially increased pressure flattening, the susceptibility of samples from different fields and cultivars to moisture loss could be predictive of pressure flattening development. The different fields and cultivars produced a range of at-harvest moisture loss susceptibility when allowed to dry in ambient conditions (20C and 40% RH) and at an accelerated rate in a drying oven set at 38 degrees C. It was thought that dry soil, and therefore tuber dehydration prior to harvest, may have a strong influence on pressure flattening development so two tests were developed to attempt to determine hydration status of the tubers at harvest. The first involved soaking tubers for 24 hours and measuring weight gain believed to result from absorption of water through the periderm. The second technique involved modifying a procedure that used short duration soaking of leaf discs to determine relative water content (Dhanda and Sethi, 1998). In our testing, tissue cores were extracted from the surface of the tubers and soaked, ideally to reach maximum hydration. Due to the influence of tuber dehydration on increased blackspot bruise incidence at harvest (Thornton and Timm, 1990) and the variability in blackspot bruise incidence when a range of fields and cultivars were tested, attempts were also made to see if percentage of tubers with blackspot bruise at-harvest would correlate with differences in pressure flattening. Research has suggested that potatoes with lower specific gravity may be more prone to pressure flattening development (Thornton and Bohl, 1998). As a result, specific gravity was measured at harvest to determine whether a correlation existed between specific gravity and pressure flattening susceptibility. The last potential at-harvest predictive test involved measurement of the maximum amount of force required to deform the surface of the tubers at harvest. This testing would be similar to testing using a penetrometer conducted with apples to determine storability. Previous research had also been conducted that determined differences in the resistance of potato tissue to force and pressure based on cultivar differences and tuber hydration (Zdunek and Umeda, 2005, Bajema et al. 1998). However, the use of a penetrometer or texture analyzer to predict relative pressure flattening was considered a novel concept.

Materials and Methods

In order to develop a method for predicting differences in potential to pressure flatten in storage there needed to be ways to obtain measurements of moisture loss at harvest coupled with the ability to evaluate whether those measurements are related to eventual pressure flattening. In 2009 and 2010, experiments were carried out to measure moisture loss at harvest, re-uptake of water by freshly harvested tubers, and blackspot bruising. In 2011, samples were tested at-harvest for relative water content using tissue cores, specific gravity and the peak load required for 3mm. deformation. These results were than compared with pressure flattening development for the respective storage seasons.

For the initial year of rehydration and at-harvest dehydration tests, one hundred and fifty tubers (228-342 g.) were harvested by hand from 16 separate commercially managed fields on the day prior to commercial harvest. These 16 fields were selected because they represented 3 different russets, 2 different yellow skinned potato cultivars, and 2 different red skinned cultivars that were thought to differ substantially in storability. The tubers were divided into three sets of five replicates of ten tubers. The samples were collected into 4.5 kg. plastic mesh bags with labels and weighed immediately after collection. One set of five bags was placed into a Grieve drying oven and dehydrated at 37 degrees C for 24 hours. A second set of five sample bags was held in ambient conditions (20 degrees C and 40% relative humidity). After 24 hours the samples were reweighed. The third set of five bags from each field /treatment was placed in a 35 l. plastic bucket filled with water at approximately 18 degrees C for 24 hours. After 24 hours the samples were re-weighed, and percentage weight gain or loss was calculated. On the day of harvest for each of the 16 fields, three 20 kg plastic mesh onion sacks were filled with approximately 12 kg of 227-340g, freshly harvested tubers and labels were placed in each sack. The filled sacks were then stored inside a climate controlled corridor at approximately 14 degrees C and 95% relative humidity while samples from the other fields were obtained during the next several days. Once the at-harvest samples were all collected, they were tied shut using 1.3 cm diameter polymer rope and taken to a 30,000 cwt. storage bin that was being filled. The operator of the piling apparatus created a flat pile of potatoes with an area approximately 1 m. high and 3.7 m. by 1.2 m. wide in the middle of the storage cellar. The sample bags were laid flat on top of this short potato pile in a randomized fashion. Additional polymer rope was then used to tie the bags closely together by threading the rope through one end and sliding them together one at a time. The excess rope that was still attached to the samples was then tied to metal railing on a catwalk above the pile. The piling line operator then resumed filling the cellar until it was uniformly filled to a height of 5 m. The blackspot bruise testing was conducted by an agricultural consulting and testing company (Agroengineering, Inc, Alamosa, Colorado USA) that evaluates all fields and cultivars grown by several local potato growers for blackspot bruising during harvest. Their procedure to test blackspot bruise susceptibility is to randomly collect approximately 10 kg. of potatoes from every 2^{nd} truckload of potatoes that arrives at the storage to be unloaded, incubate the tuber for 16 hours at 37 degrees C and then peel the tubers to determine percentage of tubers with blackspot bruising. A typical field would produce roughly twenty, 10kg. samples. The blackspot bruise results from this testing were used for the 16 combinations of fields and cultivars that were selected for study.

In 2011, a series of three at harvest tests were developed to predict relative pressure flattening susceptibility. The tests were to measure at-harvest specific gravity, at-harvest relative water content using cores cut from the potatoes surface, and determination of peak load in grams required for a 3mm surface deformation of the tubers. This testing was conducted for all treatments and cultivars in field trials in 2011, which resulted in 45 separate combinations of cultivar and treatment. Plots were mechanically harvested 3 weeks after vine kill, and 21 plastic mesh bags were used collect samples with ten 228-342 gram 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. From the remaining non-damaged tubers, samples were gathered for specific gravity, relative water content, and texture analysis testing. Specific gravity was determined using the weight in air vs. weight in water method wherein specific gravity = weight in air/(weight in air - weight in water). Three samples of ten tubers each were first weighed on a 10 kg. capacity analytical balance and then transferred to an attached metal basket that was immersed in a 190 l. plastic water barrel. Water used was allowed to equilibrate to the ambient temperature of 20 degrees C before testing. The At-harvest relative water content testing was adapted from techniques using discs of leaf tissue (Dhanda and Sethi, 1998) in which tissue samples are weighed, floated for four hours in a small container or petri dish containing water, removed and weighed again, and then placed in a drying oven to remove all water from the tissue and thereby obtain an oven dry weight. Once these weight measurements are obtained the relative water content of the tissue at harvest can be calculated using RWC = (FW-DW)/(TW-DW), where FW is the initial fresh weight, DW is the oven dried weight, and TW is the turgid weight of the samples immediately after soaking in water. Potato tubers are obviously not leaves, so for our testing, ten 1 cm. diameter by 1.5 cm. depth tissue cores were extracted using a 1 cm. diameter tubular metal hand borer from each of fifteen tubers randomly selected at harvest for each cultivar/treatment combination. The tissue cores were weighed and then placed in a 50 ml. conical plastic tube. Cold water was added to the tube until the cores were immersed and then the tubes were labeled, including the time, and placed in a test tube rack for three hours. The tubes were not handled or agitated during this time to avoid sloughing of tissue. After three hours the cores were removed from the tube, gently patted dry using a paper towel, and weighed. Then the cores were placed in an aluminum foil tray and put into a drying oven at 80 degrees C for 48 hours to remove all moisture, before being weighed again. The texture analyzer or instrumented penetrometer used to determine peak load required for surface tissue deformation was a 10 kg. capacity Brookfield CT3 Texture Analyzer 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 3mm. target deformation depth was thought to correspond well to the depth of the periderm and underlying cells that would be crushed by pressure flattening in commercial storage. An attempt to achieve greater deformation depth would likely require more force than the 10 kg. model was capable of producing. When the instrument was purchased, preliminary testing was conducted using previously stored and oven treated tuber samples, with and without removing the periderm by peeling, to determine the if the periderm itself and moisture loss had an effect on the peak load required for deformation. 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 3mm. below the 75 gram “trigger” setting. Once 3mm.deformation was 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. For the at-harvest testing of the different fields and cultivars, thirty tubers were tested. For these samples, the tuber surface was not peeled because preliminary testing determined that the skin (outer periderm) itself provided some resistance to pressure as well as because potatoes in bulk storage are stored with their skin attached.

In 2011 and 2012, additional texture analysis testing was done using tubers of 3 russet cultivars (Russet Norkotah Selection 8, Classic Russet, and Rio Grande Russet) to determine the sensitivity of the texture analyzer to moisture loss (as percent weight loss) from the tubers. The relative water content test was also evaluated in 2011 for the three russet cultivars to determine how sensitive that test was to differences in moisture loss. 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 degrees 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 (+/- 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 3mm. deformation and tested for relative water content. Immediately before the texture analysis for each potato, the tissue cores for relative water content were collected from the half of the potato not used for the texture analyzer. Extra tubers that had been re-weighed 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 4.5% 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 +/-0.15 percent 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 load.

Procedure to Induce Pressure Flattening

The samples from 2009-2010 were placed in a 5 m. high potato pile in commercial storage bin and allowed to develop pressure flattening until the bin was shipped in March. The sample bags were removed from storage and evaluated for pressure flattening as described on the next page (Evaluation of the Samples for Pressure Flattening).The 21 mesh bags set aside at harvest in 2011 were weighed, the weight recorded, and then placed into three sets of ventilated containers. Seven sample bags from each cultivar and treatment were placed in each set of ventilated containers. One set of two containers would be disassembled and the sample tubers evaluated after 3 months, another set after 6 months, and a third set after 9 months storage duration. Samples from within the same field experiment were kept in the same container. The ventilated container apparatus, as described earlier, was designed to test tuber susceptibility to pressure flattening when exposed to ventilation, time, and pile pressures similar to those found in commercial potato storages. The six filled containers were placed tightly together with a continuous air exchange tube beneath them. After the desired storage duration, sample bags were removed from the containers, weighed to determine weight moisture loss during storage and then assessed for pressure flattening. The set of samples stored for 9 months in 2011 was discarded due to excessive sprouting. The samples had not been treated with sprout inhibitors because the containers were being kept in a storage normally used to store seed potatoes.

An initial evaluation of the effects of simulated pile heights is being conducted in 2012-2013. Tubers from 15 different cultivars were evaluated for peak load required for 3mm surface deformation at harvest. Six ventilated containers were used, to allow for three different pile heights (3.1 meters, 3.7 meters, and 4.6 meters) at 2 different storage durations (3 month and 6 month). 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 is used to provide additional weight. The differences in the fill level of the tanks would allow for pressures on the samples to change, creating the different simulated pile heights. The comparisons between at-harvest peak load and the resulting pressure flattening per tuber are presented with the data on use of texture analysis.

Evaluation of the Samples for Pressure Flattening

Pressure flattening was evaluated for each tuber within each sample bag. Tubers were visually inspected and each flattened area was circled, numbered in ascending order using permanent markers, and its diameter measured. 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 227-340g tuber which has more than 18 cm^2 combined flattened area is beyond the grade tolerances established for a US No. 1 or US No. 2 potato. The samples evaluated in 2009-2010 were recorded as the percentage of tubers that had no observable pressure flattening, the percentage that had pressure flattening but were still acceptable as a US No. 1 potato, and the percentage of tubers that had pressure flattening that would reduce the quality of the potato to a US No. 2 or below. In 2010 and 2011, individual flattened areas were measured and averaged for each sample bag, with the number of bags serving as a replicate. Pressure flattening from those experiments is presented as the averaged pressure flattened area per tuber.

Statistical Analysis and Design

Tubers that were tested or subjected to pressure flattening were randomly selected from among 227-340g. 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 α=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. Correlations are based on an automatically calculated logarithmic trend line for comparing two sets of plotted data using Microsoft Excel 2007. The R-squared values displayed in the figures were also calculated by Excel. Error bars in figures and means separation in tables using letter based groupings are based on a calculated Fishers LSD at α=0.05 using the standard error for the LS means and an approximated T-value of 2.

Results

The rate of weight (moisture) loss under ambient conditions correlated to the rate of weight loss from the oven dried samples from the same field (R^2=0.5896) (Figure 7). This indicates that use of the drying oven to determine moisture loss susceptibility could provide more dramatic and easily observable differences between cultivars and fields while maintaining similar relative moisture loss to that which is likely to occur during harvest and early storage.

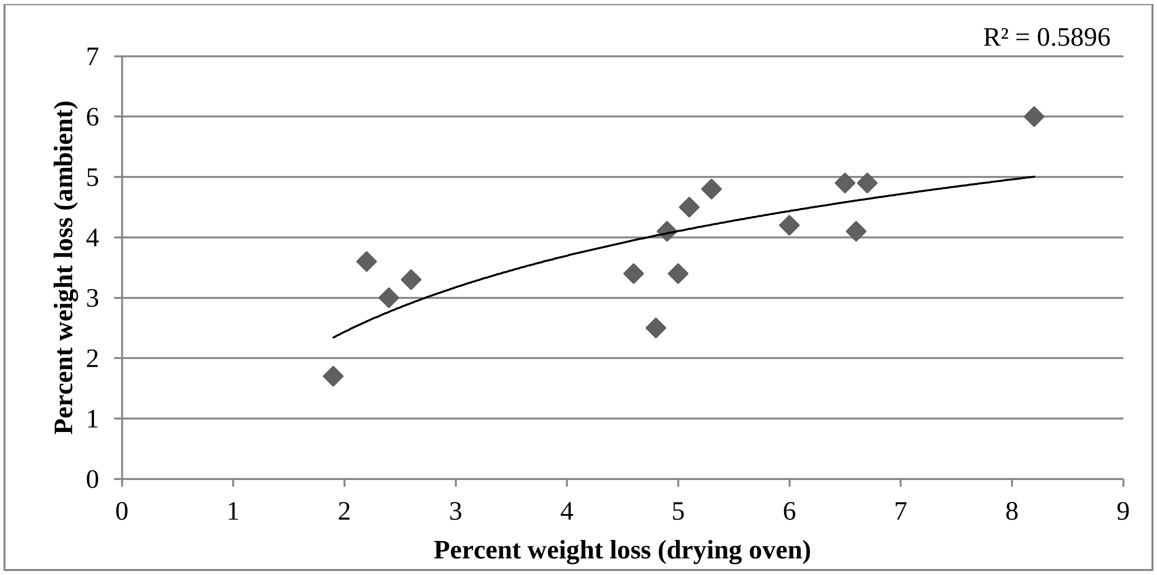

Figure 7. Correlation of percent moisture loss of sets of at harvest samples that were either allowed to lose moisture for 48 hours under ambient conditions (20°C and 45% relative humidity) or for 24 hours in a drying oven at 37°C). The R-squared value for the correlation trend line is in the upper right corner of the figure.

Table 2 indicates differences in all at harvest measurements between cultivars and in some instances between fields within a cultivar. The field of Classic Russet and Mozart Field C were more susceptible to blackspot bruise than all Innovator fields Satina fields or Yukon Gold Fields. Additionally, Innovator Field B, Red Star, and Satina Field A had less blackspot bruising than Fields A or B of Russet Norkotah. Blackspot bruise results appear to result mostly from differences between different cultivars. Oven moisture loss results indicated significantly lower moisture loss susceptibility for Innovator Field A compared to Innovator Field B and Yukon Gold Fields A and C compared to Yukon Gold Field B.Russet Norkotah Field C also had significantly higher moisture loss compared to Innovator Field B or Yukon Gold Fields A and C.

The amount of weight gain due to immersion in water was variable enough that significant differences were observed. One challenge of rehydrating the potatoes is that samples with very poor skin set appear to show high water uptake that may be more related to skin set than to the hydration status of the tubers.

This was likely the case for the cultivar Mozart, which across all three fields had significantly more weight gain than Red Star,Russet Norkotah Field A, and Satina Field A.

Table 2**.** Weight loss (moisture loss) measurements and blackspot bruise results from at-harvest testing (by percent).

Field	**Cultivar**	**% Oven loss**	**% Water gain**	**% Blackspot Bruise**
A	Classic Russet	5.1 AB	1.7 AB C	24 D
A	Innovator	8.4 B	2.0 BC	12 AB
B	Innovator	2.4 A	1.7 ABC	2 A
A	Mozart	5.3 AB	2.6 C	11 ABC
B	Mozart	4.6 AB	2.6 C	11 ABC
C	Mozart	6.0 AB	2.7 C	17 D
A	Norkotah	6.5 AB	0.5 A	15 CD
B	Norkotah	6.7 AB	1.3 ABC	14 BCD
C	Norkotah	8.4 B	1.7 ABC	9 ABCD
A	Red Star	5.0 AB	0.9 AB	3 A
A	Satina	6.6 AB	1.0 AB	4 AB
B	Satina	4.9 AB	1.3 ABC	5 ABC
C	Satina	4.8 AB	1.4 ABC	3 A
43	Yukon	1.9 A	1.7 ABC	5 ABC
53	Yukon	8.2 B	2.3 BC	5 ABC
55	Yukon	2.6 A	1.6 ABC	6 ABC

The pressure flattening results from the samples stored in the commercial storage until March are compared in Table 3. More scorable pressure flattening was observed for Classic Russet (63%) and Yukon Gold Fields A and B (57% and 48% respectively) compared to the two Innovator Fields, the three Satina Fields, Russet Norkotah Field A, Yukon Gold Field C, and Mozart Field B. The only significant difference in the non-scorable results was between the Classic Russet field (36%) and Yukon Field A were among the lowest compared to Mozart Field B (75%) and Innovator Field A with (70%). This is largely due to fact that the remainder of the Classic Russet tubers and Yukon Field A tubers had severe pressure flattening. The table could also be interpreted to show that potatoes in the lower half of a 5 m. pile of potatoes are likely to have pressure flattening (even if non-scorable if stored for several months). Please note the explanation for scorable and nonscorable pressure flattening below the table.

Table 3**.** Total at harvest moisture loss, blackspot bruise, and March pressure flattening results (by percent).

Field	**Cultivar**	**%Flattening non-scorable**	**% Flattening scorable**
A	Classic Russet	36 A	63 D
A	Innovator	70 BC	20 ABC
B	Innovator	62 ABC	0 A
A	Mozart	47 ABC	33 ABCD
B	Mozart	75 C	5 A
C	Mozart	63 ABC	28 ABCD
A	Norkotah	50 ABC	13 AB
B	Norkotah	63 ABC	30 ABCD
C	Norkotah	50 ABC	38 ABCD
A	Red Star	58 ABC	25 ABCD
A	Satina	51 ABC	16 A
B	Satina	62 ABC	5 A
C	Satina	54 ABC	17 AB
A	Yukon	40 AB	57 CD
B	Yukon	51 ABC	48 BCD
C	Yukon	52 ABC	35 ABC

***Percent flattening nonscorable is the percent of tubers that had small pressure flattening that would not be scored as damage by USDA. Percent scorable flattening is the combined total of potatoes that would be damaged enough to be graded as No. 2 or lower.

The percent of tubers with more severe, scorable pressure flattening compared to the percent of weight loss (as moisture loss) from the drying oven for the fields and cultivars is plotted in Figure 8. Despite the logic that immature tubers were more likely to lose moisture and therefore pressure flatten more severely, there was no significant correlation between oven moisture loss and pressure flattening.

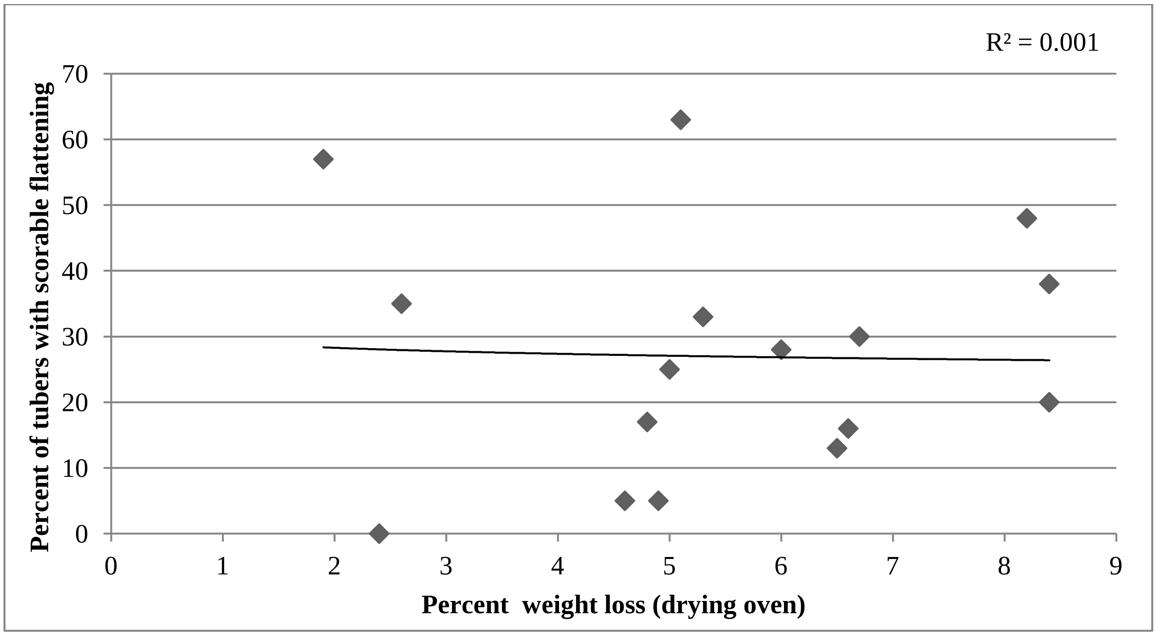

Figure 8. Correlation of moisture loss susceptibility (24 hours at 37°C) with percent of tubers that developed pressure flattening in excess of the USDA No. 1 quality standard after 5 months storage in a commercial storage bin. The R-squared value for the correlation trend line is in the upper right corner of the figure.

The percent weight loss from the drying oven treatment was plotted against the percent weight gain from the rehydration treatment to determine if fields and cultivars that had greater moisture loss in the oven were more (or less) likely to absorb more water when immersed (Figure 9). In other words, it was important to determine if sampled fields were losing less weight in the oven because they had previously been dehydrated in the field (resulting in an increase in weight gain from rehydration). For the fields and cultivars studied there appeared to be no relationship between the oven weight loss treatment results and the weight gained during rehydration. In addition, there was no correlation observed when the percent weight gain from rehydration is compared to the percent of tubers with scorable pressure flattening (Figure 10).

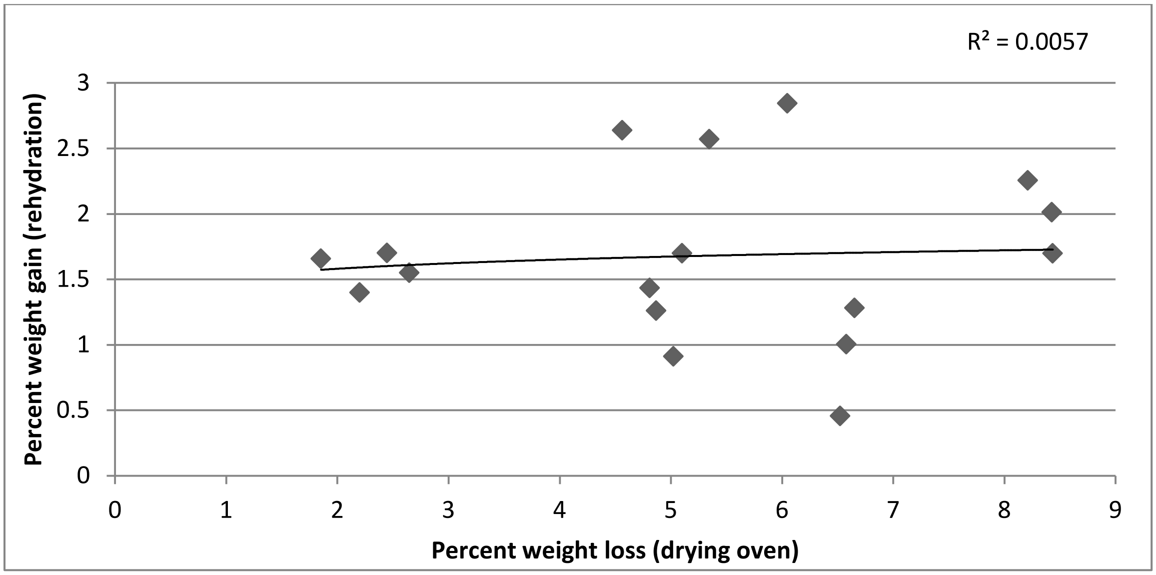

Figure 9. Correlation of percentage of water uptake of samples at harvest (as increase in mass) after immersion in 20°C water for 24 hours compared with percent moisture loss when stored at 37°C for 24 hours. The R-squared value for the correlation trend line is in the upper right corner of the figure.

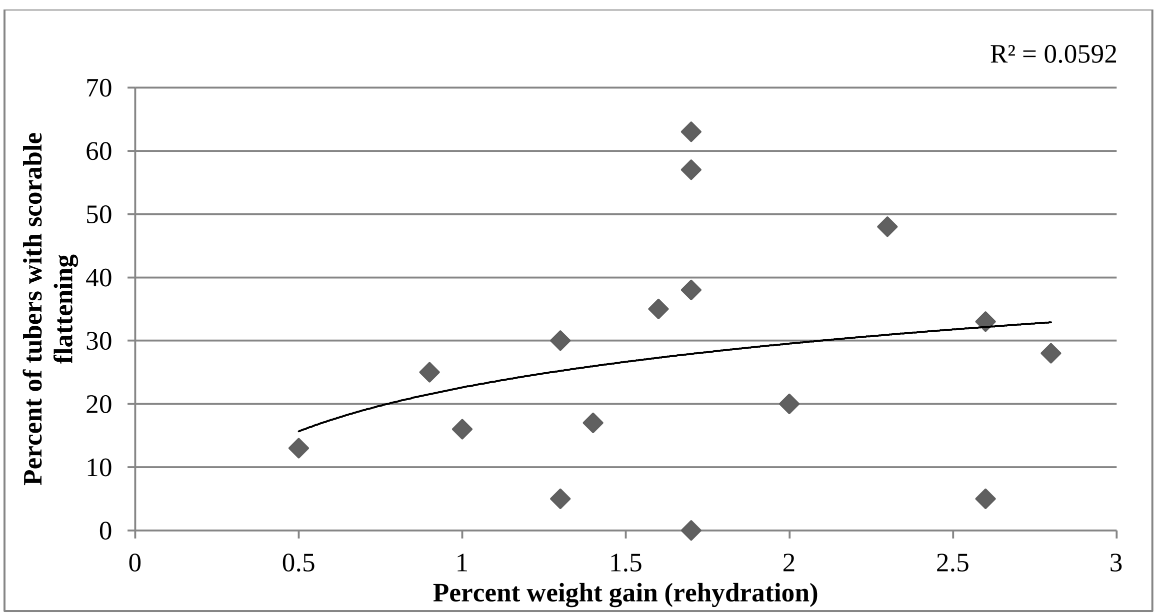

Figure 10. Correlation of percentage of water uptake of samples at harvest (as increase in mass) after immersion in 20°C water for 24 hours compared with percent of tubers that developed pressure flattening in excess of the USDA No. 1 quality standard after 5 months storage in a commercial storage bin. The R-squared value for the correlation trend line is in the upper right corner of the figure.

A graphical comparison of increasing percentage of tubers with scorable pressure flattening against the percentage of tubers with blackspot brusing at harvest is represented in Figure 11. Although the field with the most blackspot bruise (Classic Russet) also had the most scorable pressure flattening, there is no obvious trend showing a relationship between blackspot bruise and percent scorable flattening across fields and cultivars. When the data is plotted to determine if there is a correlation between blackspot bruise at- harvest and scorable pressure flattening there was no correlation (Figure 12).

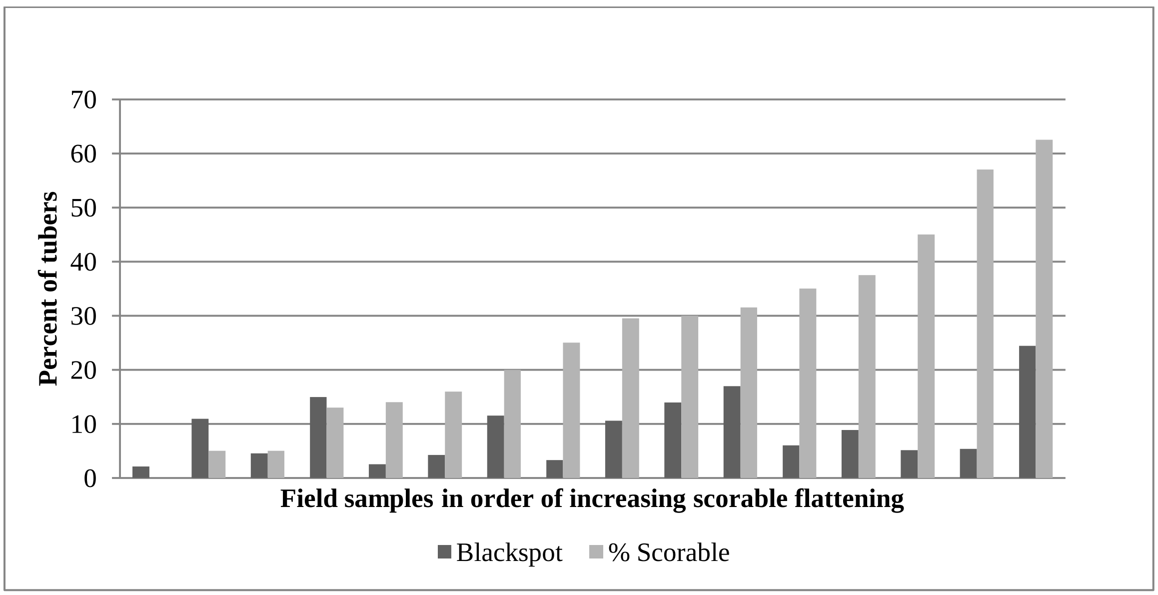

Figure 11. Comparison of percentage of tubers with blackspot bruise across fields and cultivars with the percentage of tubers that developed pressure flattening in excess of the USDA No. 1 quality standard after 5 months storage in a commercial storage bin arranged in order of increasing pressure flattening.

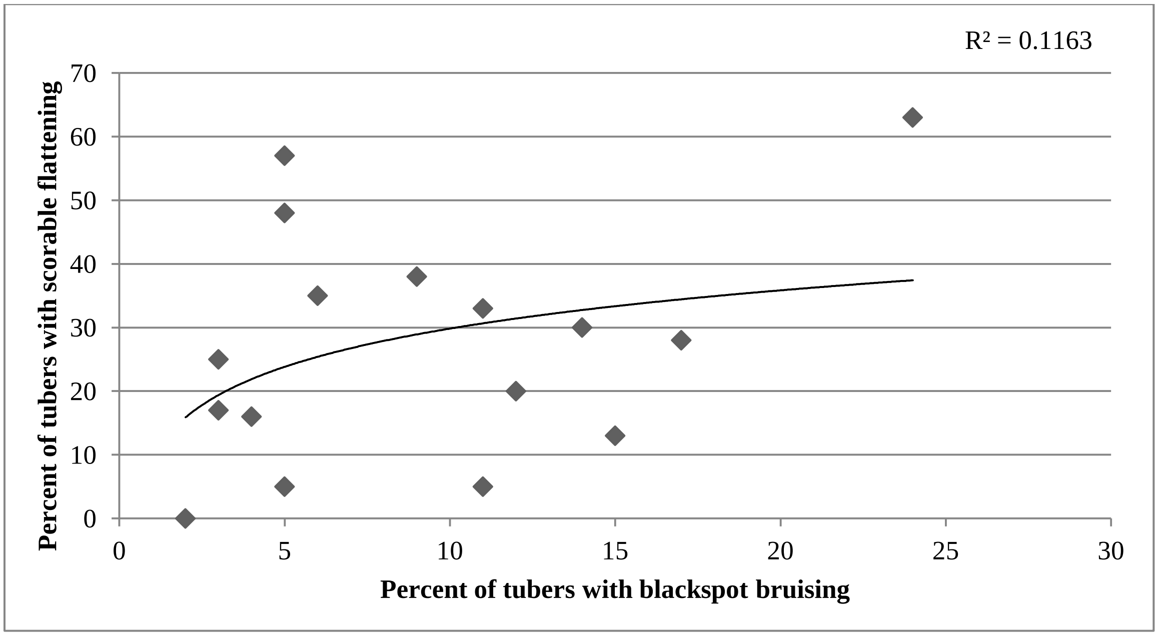

Figure 12. Correlation of percentage of tubers with blackspot bruise at with percent of tubers that developed pressure flattening in excess of the USDA No. 1 quality standard after 5 months storage in a commercial storage bin. The R-squared value for the correlation trend line is in the upper right corner of the figure.

In 2011, there was a different series of at-harvest predictive tests conducted to anticipate relative pressure flattening development for forty four combinations of russet cultivars and treatments. At-harvest specific gravity results showed low correlation (R^2=0.2404) with the pressure flattened area per tuber after three months storage in the ventilated containers (Figure 13). There was a similar small correlation (R^2=0.2026) for the at-harvest specific gravity compared with the pressure flattened area per tuber after 6 months storage duration using the ventilated containers system (Figure 14).

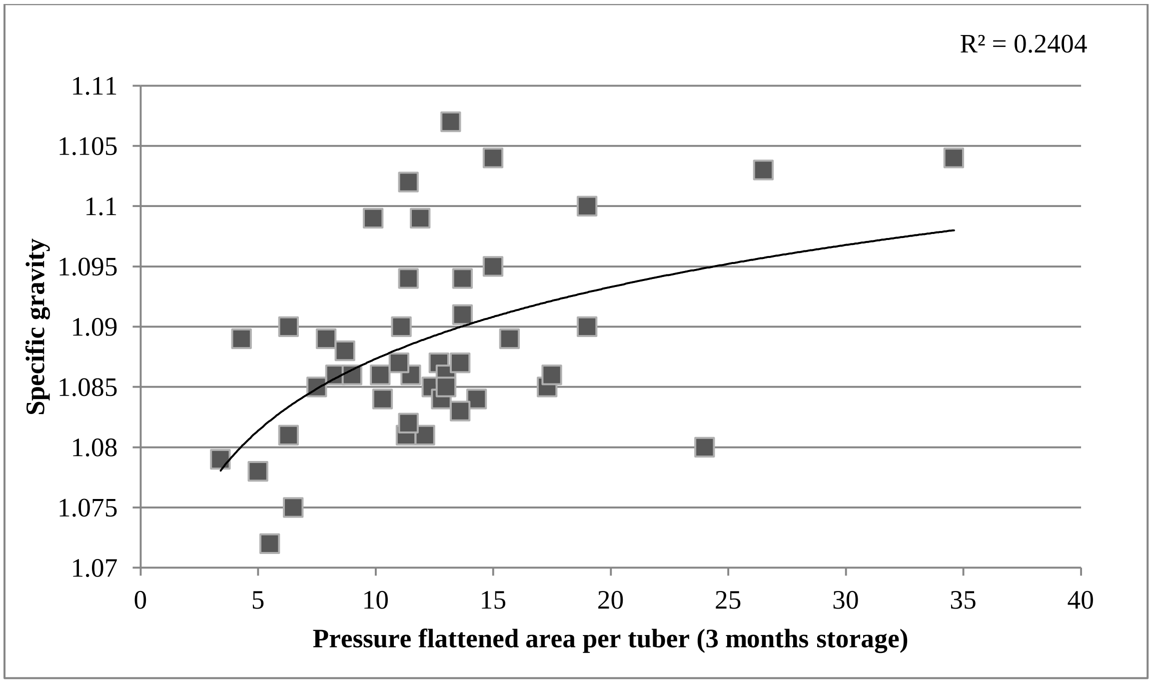

Figure 13. Correlation of at harvest specific gravity of tubers with the pressure flattened area per tuber (cm^2) after 3 months storage duration. The R-squared value for the correlation trend line is in the upper right corner of the figure.

The change in relative water content did show a downward trend as tuber moisture loss increased (Figure 15). However, it does not appear that, at least using our methodology, relative water content testing of tuber tissue cores would be sensitive enough to correctly identify differences in tuber weight loss in 1% increments.

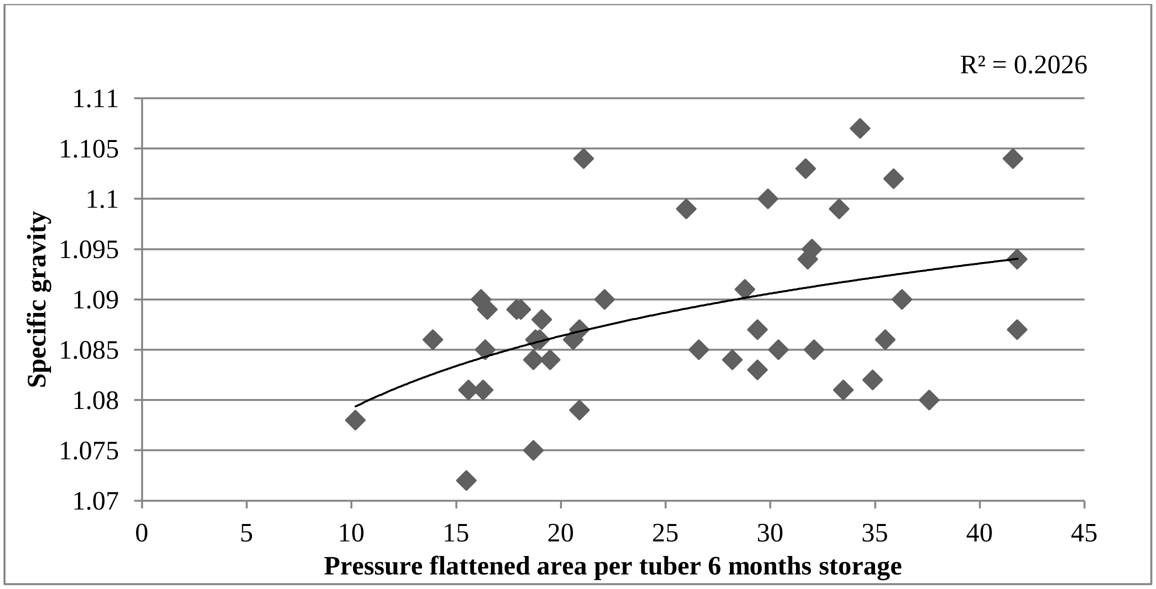

Figure 14. Correlation of at harvest specific gravity of tubers with the pressure flattened area per tuber (cm^2) after 6 months storage duration. The R-squared value for the correlation trend line is in the upper right corner of the figure.

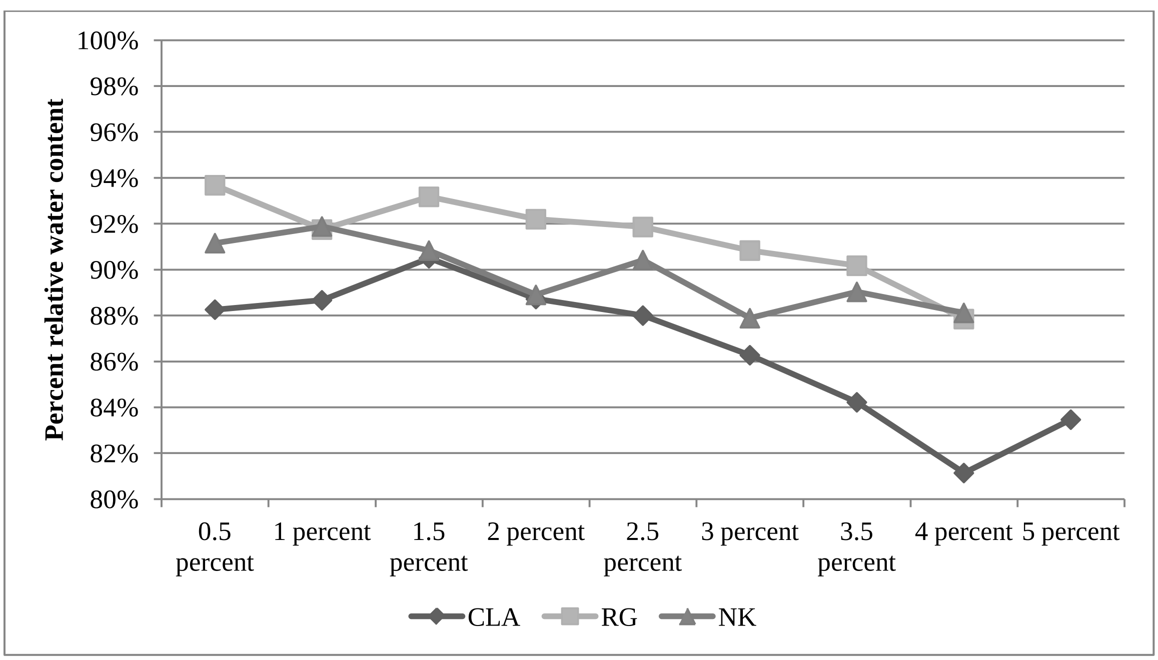

Figure 15. Change in relative water content as percentage as tuber moisture loss increases (2011 data).

There is low to medium correlation (R^2 =0.3230) between the relative water content taken at harvest and the resulting pressure flattening after three months storage duration (Figure 16). This indicates that at least some differences in at-harvest moisture content between cultivars and treatments resulted in increased pressure flattening after 3 months in storage and were observable as differences in the results of the at-harvest relative water content testing. There was only low correlation (R^2=0.1742) when the relative water content results observed at harvest were compared to the resulting differences in pressure flattening after 6 months storage (Figure 17).

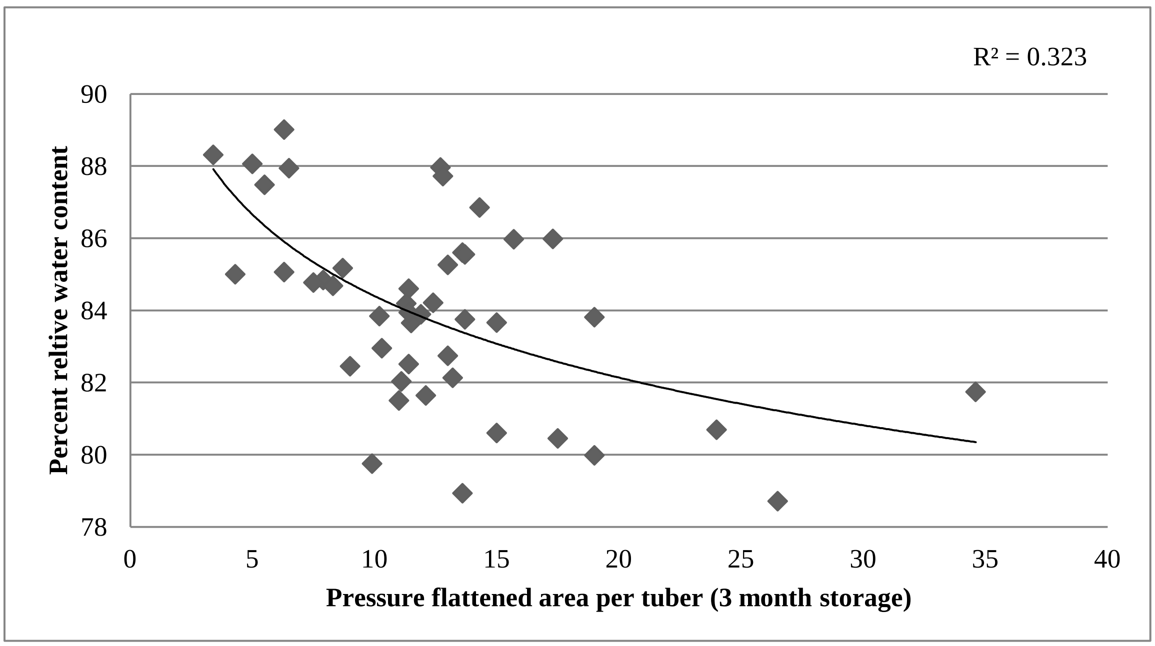

Figure 16. Correlation of at harvest relative water content of tuber tissue cores with the pressure flattened area per tuber (cm^2) after 3 months storage duration. The R-squared value for the correlation trend line is in the upper right corner of the figure.

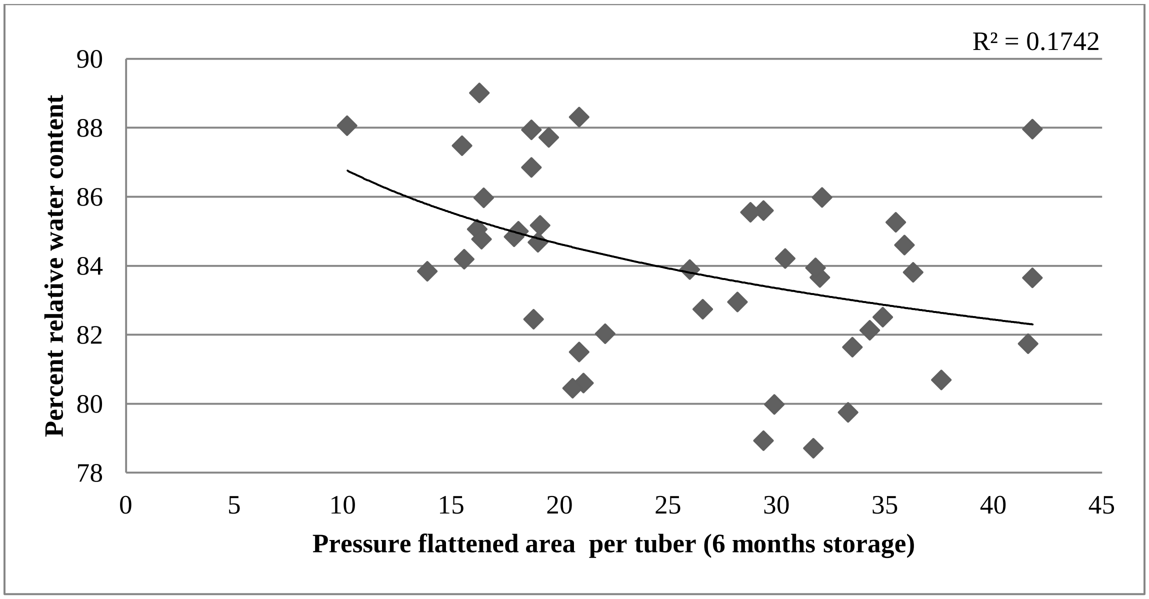

Figure 17. Correlation of at harvest relative water content of tuber tissue cores with the pressure flattened area per tuber (cm^2) after 6 months storage duration. The R-squared value for the correlation trend line is in the upper right corner of the figure.

The results of preliminary testing with the texture analyzer are presented in Figure 18. The trend of the data indicated that the peak loads required for 3mm. deformation did decrease 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 commercial storage which is why the peak load values are much lower than those expected from at-harvest testing.

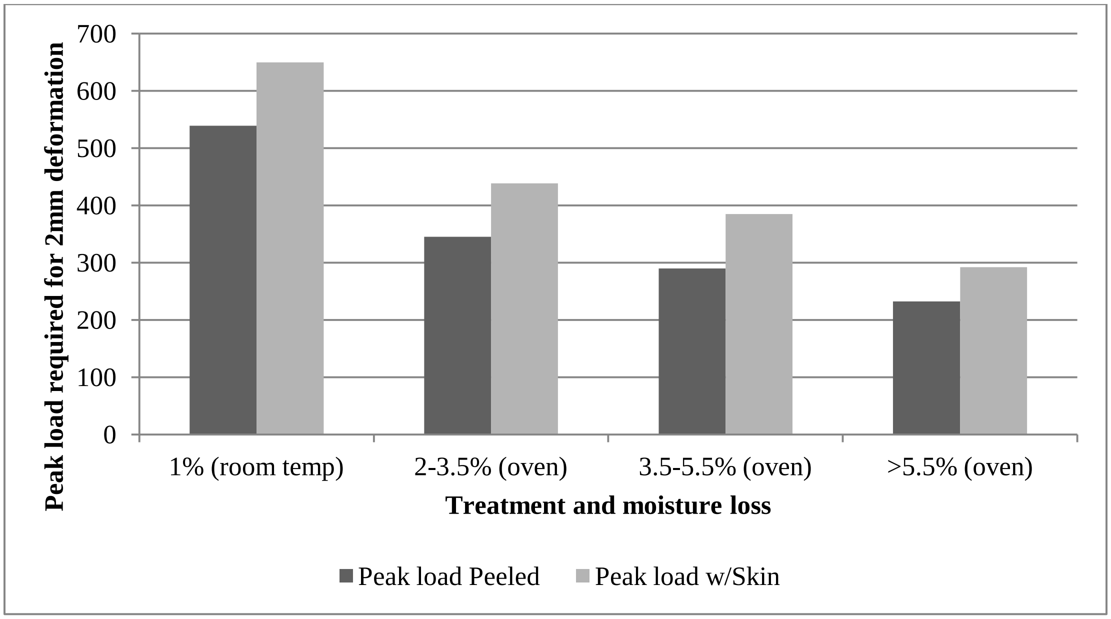

Figure 18.Change in peak load required for 2mm tuber surface deformation of post storage tubers with additional moisture loss treatments. Tubers were tested with skin intact and with skin removed.

The texture analyzer was then used in 2011 and 2012 to evaluate the change in peak load required for 3mm 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 (Figure 19). However, a likely cause of the lack of decrease in peak load between 0.5 and 1.5% moisture loss was that many samples had resistance to deformation in excess of the texture analyzer's testing capacity and had been counted as 10,000 g. even if the actual force required had been higher (Figure 20). The number of samples out of twenty tubers that were above the maximum peak load declined precipitously as weight loss increased from 0.5% to 2.0%.

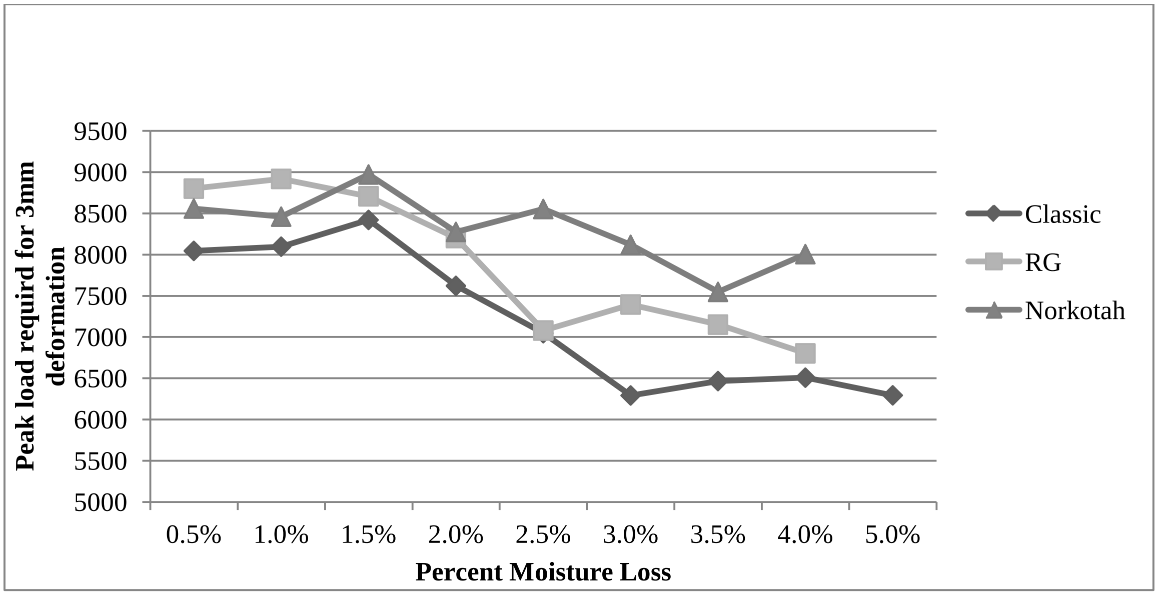

Figure 19. Change in at harvest peak load required for 3mm tuber surface deformation as tubers lost moisture following harvest from moist soil (2011 data).

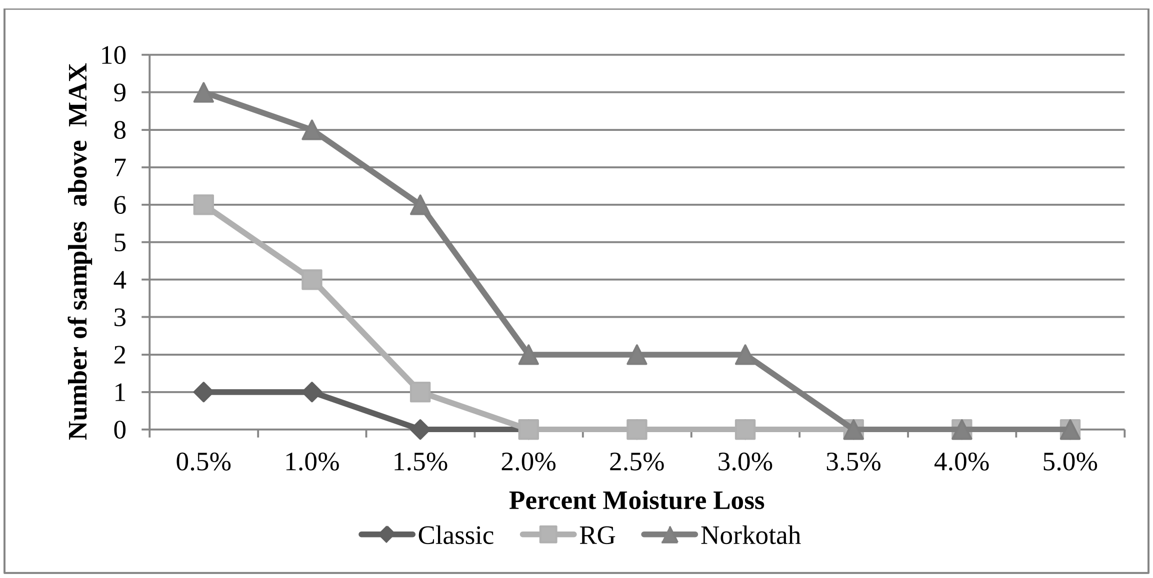

Figure 20. Number of at –harvest samples (out of 20) with a peak load required for 3mm tuber surface deformation that exceeded the 10kg. limit of the texture analyzer as tubers lost moisture following harvest from moist soil (2011 data)

Results of similar testing in 2012 when a 25kg. 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 (Figure 21). 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.

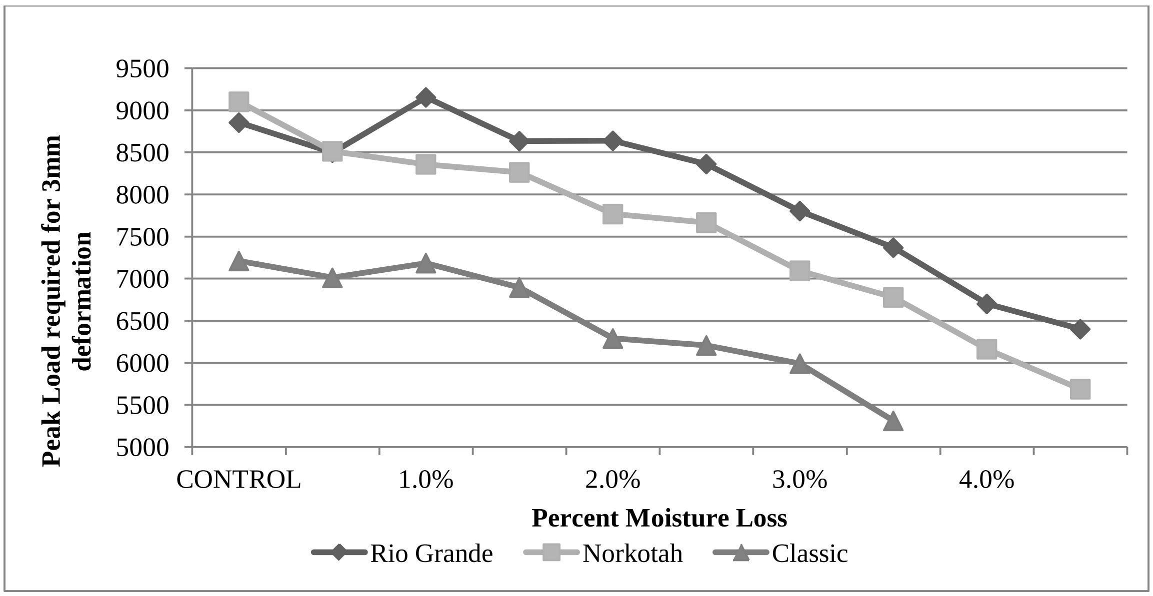

Figure 21. Change in at harvest peak load required for 3mm tuber surface deformation as tubers lost moisture following harvest from moist soil (2012 data).

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 treatment and cultivars used in field trials in 2011 (Figure 22), there were statistically significant differences among the peak load values at harvest. When the peak loads are compared to the resulting pressure flattened area after three months storage in the ventilated containers there is moderate correlation (R^2=0.3895) as shown in Figure 23.

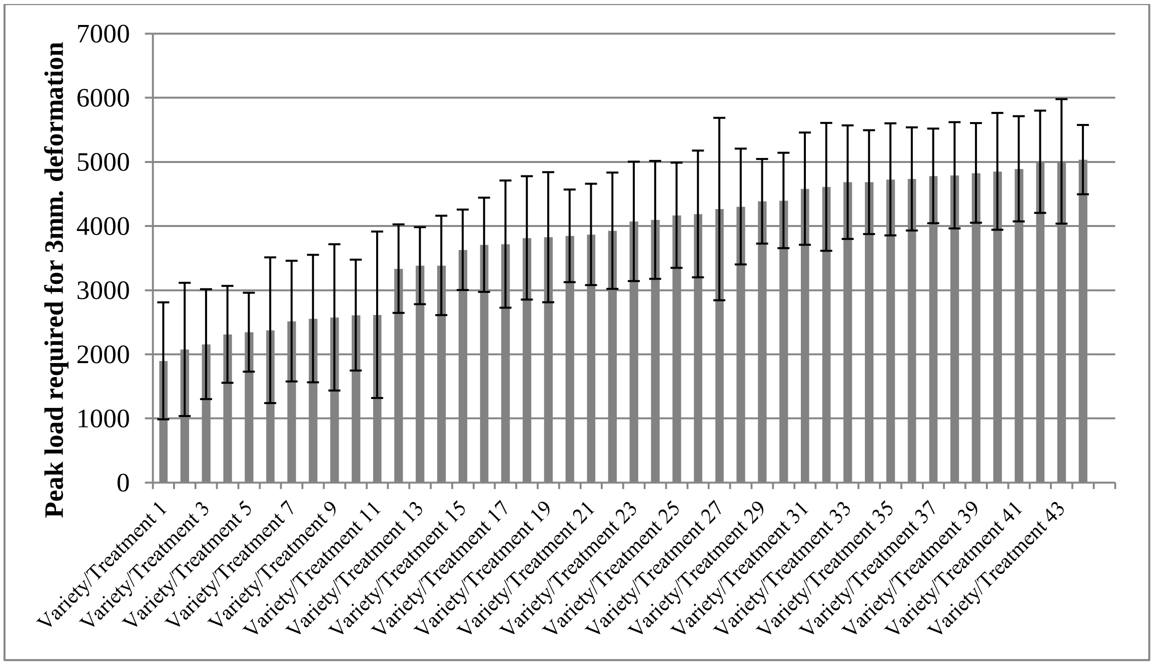

Figure 22. Comparison of at-harvest peak loads required to cause 3mm surface deformation across treatments and cultivars from 2011 field research trials.

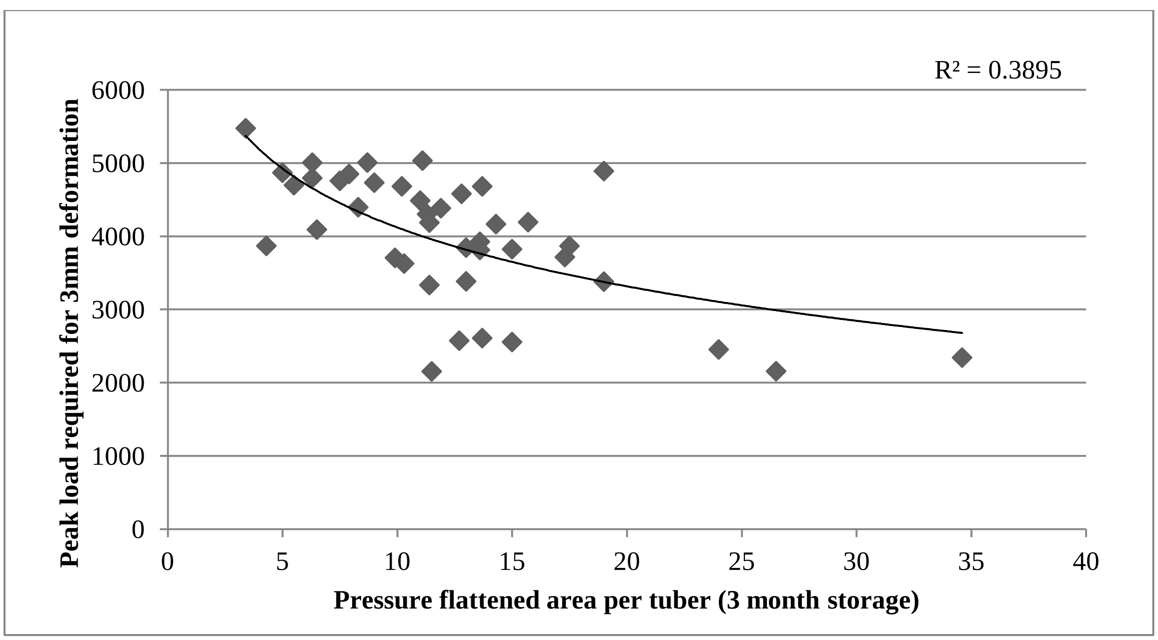

Figure 23. Correlation of at harvest peak load required for 3mm surface deformation with the pressure flattened area per tuber (cm^2) after 3 months storage duration. The R-squared value for the correlation trend line is in the upper right corner of the figure.

Because of the moderate correlation 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 form the bottom half of fields after 3 months storage. The results in Figure 24 demonstrate that, as a group, the fields 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 storage.

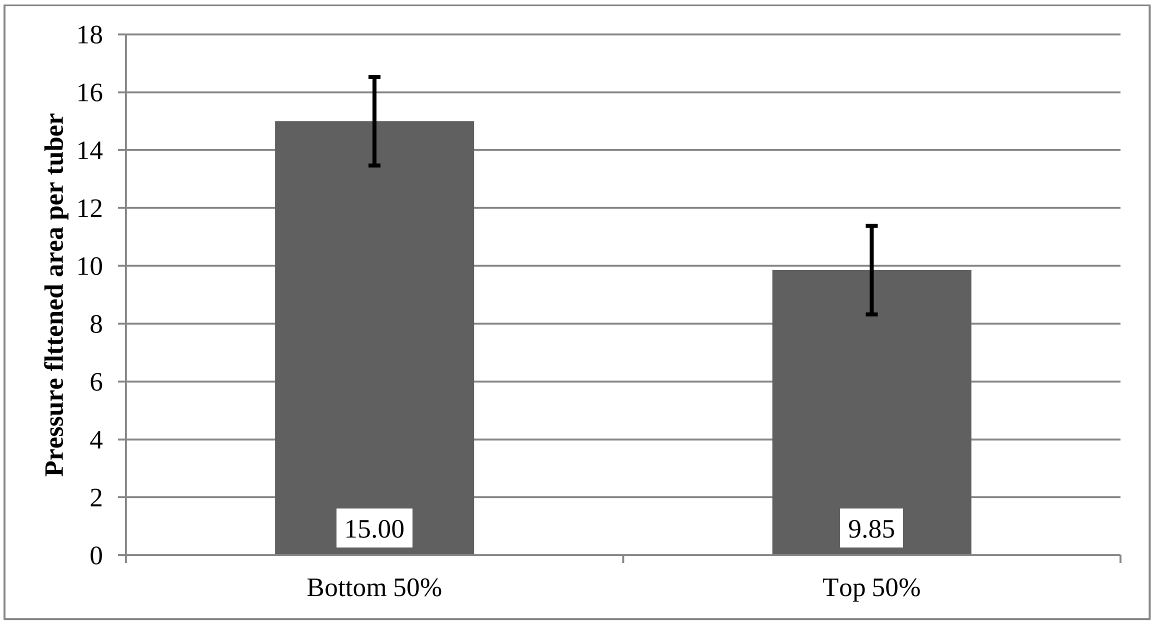

Figure 24. Comparison of averaged pressure flattened area per tuber (cm^2) across treatments and cultivars after 3 months storage duration for 2011 field experiments. “Bottom half” treatment is the average of samples that were in the lower half of values when arranged in order of increasing peak load required for 3mm. surface 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 3mm surface deformation at harvest.

Next a similar comparison was conducted by organizing the fields and cultivars into quartiles by ascending peak load, each consisting of 11 fields (Figure 25). When analyzed by quartile, the fields with lowest at-harvest peak loads produced approximately twice as much pressure flattened area per tuber after 3 months storage compared to the fields in the highest quartile (8.33 cm^2 vs. 17.01 cm^2).

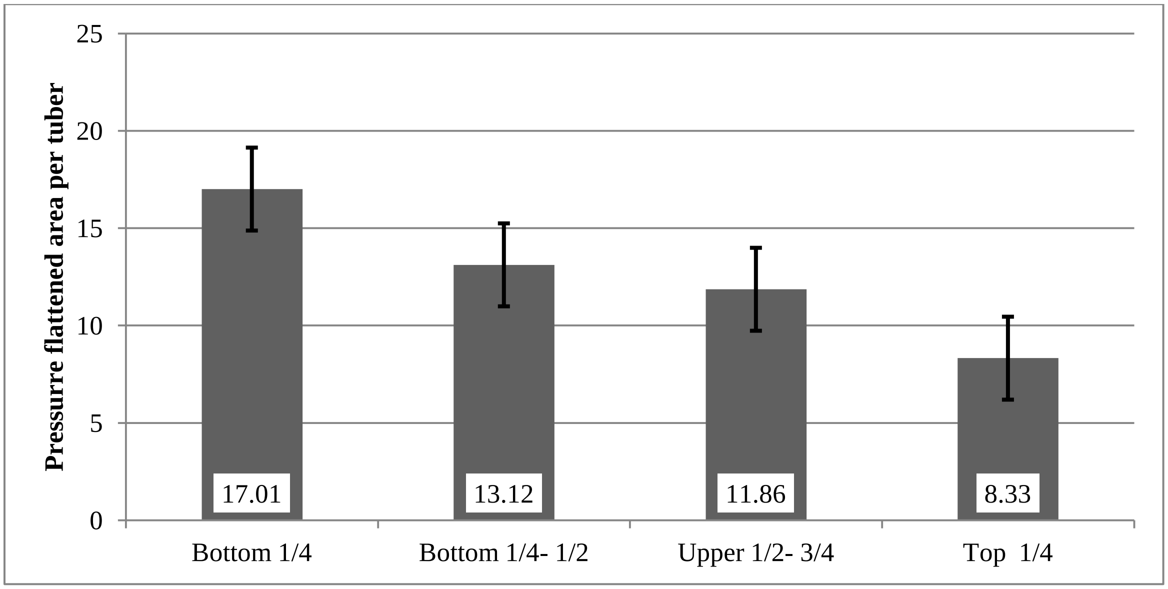

Figure 25. Comparison of averaged pressure flattened area per tuber (cm^2) across treatments and cultivars after 3 month storage duration for 2011 field experiments. “Bottom 1/4” treatment is the average of samples that were in the lower 25% of values when arranged in order of increasing peak load required for 3mm. surface deformation at harvest. “Bottom 1/4-1/2 ” treatment 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 3mm. surface deformation at harvest. “Upper 1/2-3/4” treatment is the average of samples that were in the upper 50%-75% of values when arranged in order of increasing peak load required for 3mm. surface deformation at harvest. “Top 1/4” treatment is the average of samples in the upper 25% of values when arranged in order of increasing peak load required for 3mm surface deformation at harvest.

The at-harvest peak loads for the 2011 samples were also compared to the pressure flattened area per tuber after 6 months storage duration (Figure 26). The results indicate a moderate to strong correlation (R^2=0.5481) between at-harvest peak load and pressure flattening development after 6 months storage.

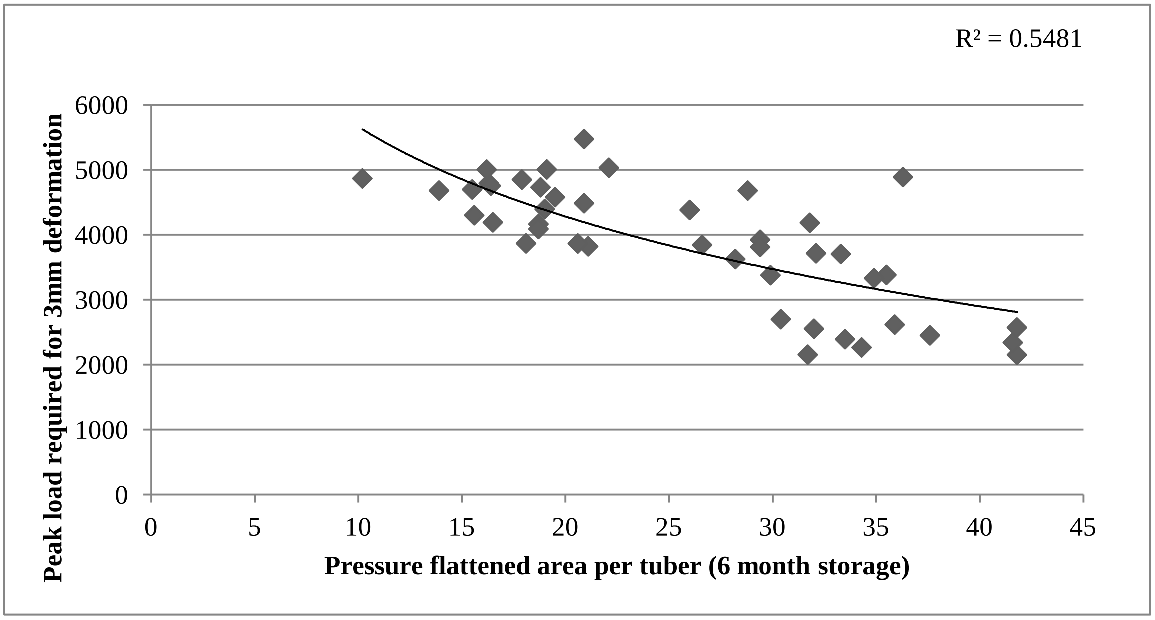

Figure 26. Correlation of at harvest peak load required for 3mm surface deformation with the pressure flattened area per tuber (cm^2) after 6 months storage duration. The R-squared value for the correlation trend line is in the upper right corner of the figure.

There was a significant increase in pressure flattened are per tuber between the upper half of fields and cultivars when organized by peak load and the bottom half of fields and cultivars (Figure 27). The pressure flattened area per tuber was 19.96 cm^2 for the fields with higher peak load values at-harvest and 31.8 cm^2 for the fields with lower peak load values.

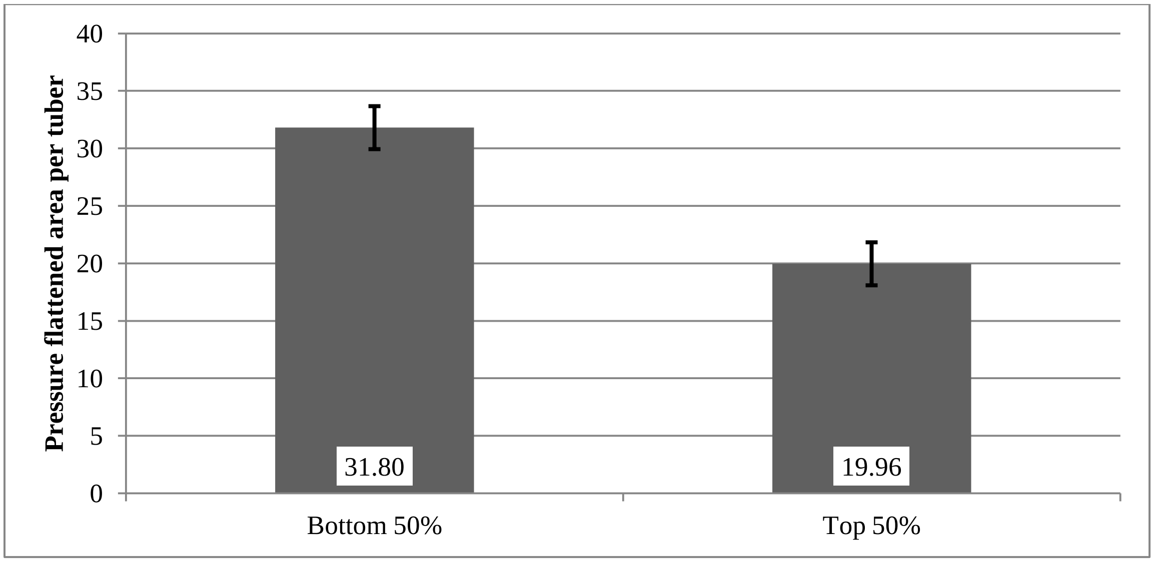

Figure 27. Comparison of averaged pressure flattened area per tuber (cm^2) across treatments and cultivars for 2011 field experiments after 6 months storage. "Bottom half" treatment is the average of samples that were in the lower half of values when arranged in order of increasing peak load required for 3mm. surface 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 3mm surface deformation at harvest.

The results for the 6 month duration samples also indicated significant differences in pressure flattened area per tuber when different quartiles of the fields were compared (Figure 28). 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 storage compared to the lower two quartiles. There was also a statistically significant difference in pressure flattened area per tuber between the bottom two quartiles, with the lowest quartile producing more flattened area (35.95 cm^2) than the next lowest quartile (27.65 cm^2).

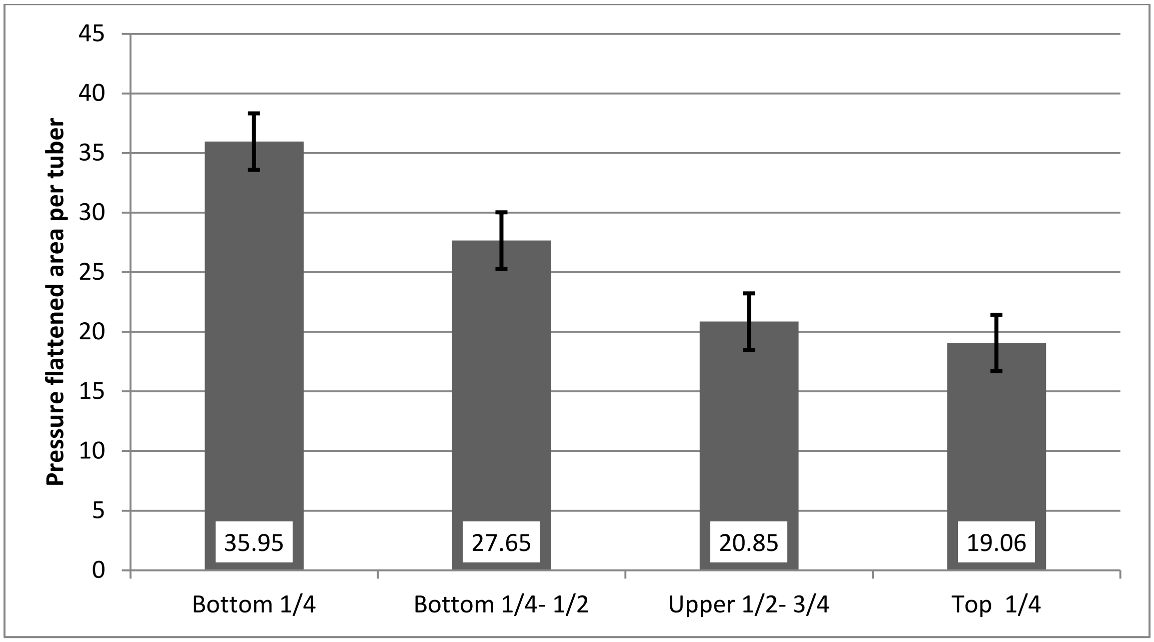

Figure 28. Comparison of averaged pressure flattened area per tuber (cm^2) across treatments and cultivars after 6 months storage duration for 2011 field experiments. “Bottom 1/4” treatment is the average of samples that were in the lower 25% of values when arranged in order of increasing peak load required for 3mm. surface deformation at harvest. “Bottom 1/4-1/2 ” treatment 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 3mm. surface deformation at harvest. “Upper 1/2-3/4” treatment is the average of samples that were in the upper 50%-75% of values when arranged in order of increasing peak load required for 3mm. surface deformation at harvest. “Top 1/4” treatment is the average of samples in the upper 25% of values when arranged in order of increasing peak load required for 3mm surface deformation at harvest.

A similar analysis of pressure flattening development compared with at- harvest peak loads was conducted for an experiment 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 Figure 29 and Figure 30. In Figure 29, there was a strong 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 storage in a simulated 3.1 m. bulk potato pile. There was a moderate correlation (R^2=0.3346) between the peak load for the 15 cultivar samples and the pressure flattened area per tuber after 3 months storage at a simulated pile height of 4.6 m. (Figure 30).

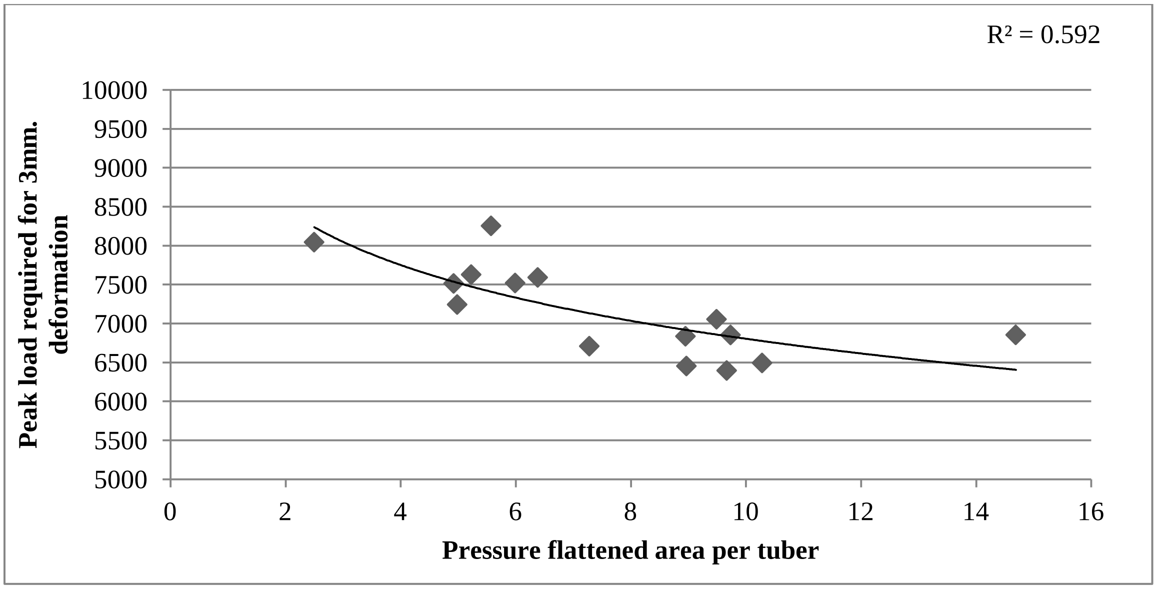

Figure 29. Correlation of 3 month storage duration pressure flattening (cm^2) for an equivalent 3.1 m. high pile with at-loading peak load for 3mm surface deformation.

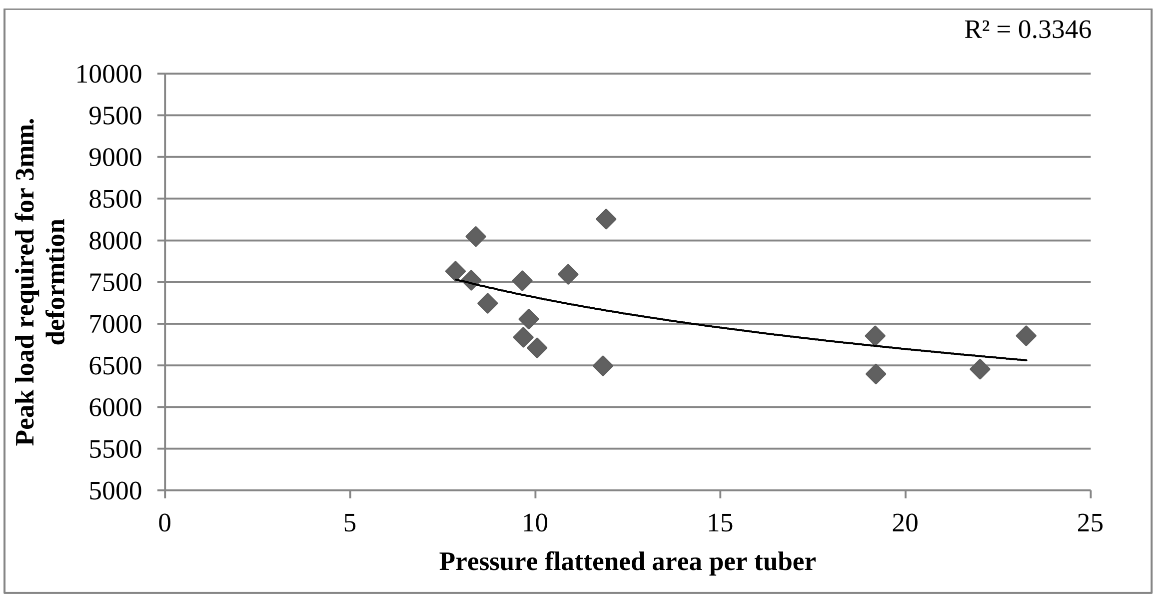

Figure 30. Correlation of 3 month storage duration pressure flattening (cm^2) for an equivalent 4.6 m. high pile with at-loading peak load for 3mm surface deformation. The R-squared value for the correlation trend line is in the upper right corner of the figure.

When the different cultivars are 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 for 3 months storage duration (Figure 31).

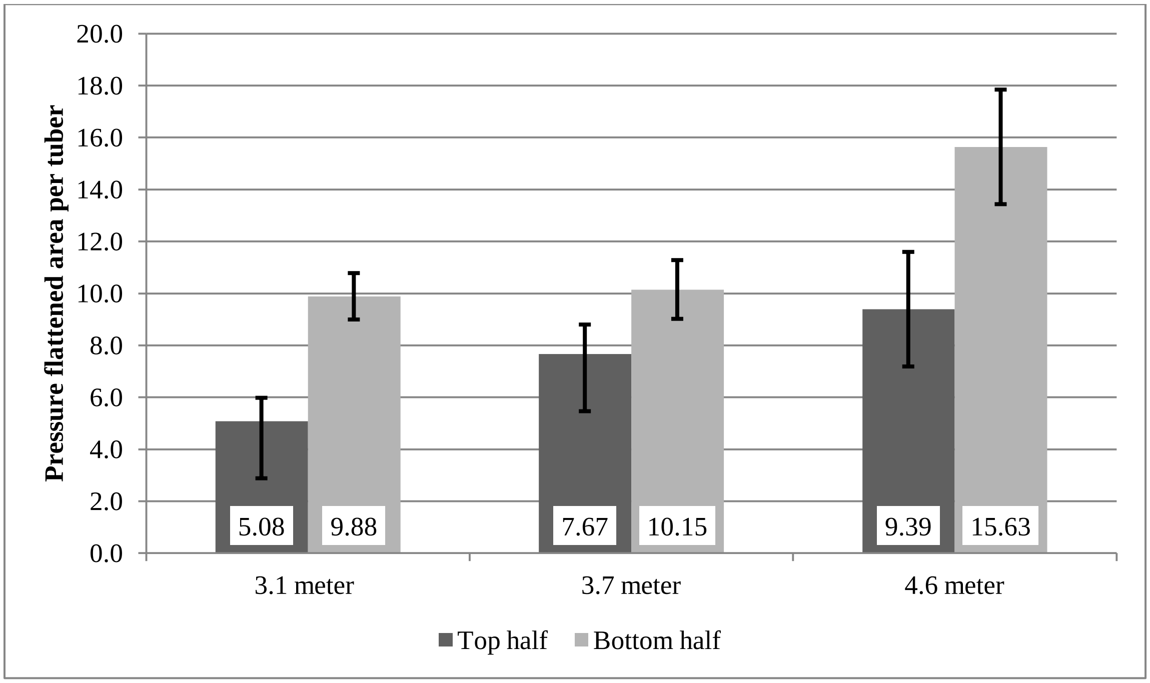

Figure 31. Comparison of averaged pressure flattened area per tuber (cm^2) by pile height. “Bottom half” treatment is the average of samples that were in the lower half of values when arranged in order of increasing peak load required for 3mm. deformation at harvest. “Top half” treatment is the average of samples in the upper half of values when arranged in order of increasing peak load required for 3mm deformation at harvest.

SECTION 3. EVALUATION OF GROWING SEASON METHODS TO REDUCE PRESSURE FLATTENING

Introduction

The physiological disorder, pressure flattening is a major cause of economic losses in cellar stored potato tubers. This complex physiological disorder is also referred to as pressure bruise. Pressure flattening refers to the development of depressed or sunken areas on stored tubers (Rowe et al. 1993). These damaged areas may also result in a grey or black discoloration in the tissue under the skin (Lulai et al. 2000). Pressure flattening accounts for a substantial portion of the $298 million dollars in lost due to potato bruising each storage year in the United States (Baritelle et al. 2000, Rowe et al.1993). Economic losses from pressure flattening result from inability to meet the USDA grade tolerance causing a reduction in value for the potatoes as they are downgraded from US No.1 to US No. 2 or lower. Pressure flattening can result in a substantial portion of a storage cellar being discarded as cull potatoes in order to meet a desired USDA grade tolerance for the remaining tubers. Pressure flattening occurs as the tuber surface becomes depressed or flattened due to constant contact with an adjacent tuber. This contacted area receives the force exerted by the adjacent tuber as a result of the weight of tubers above it in the pile, which increases as pile height increases. This pile pressure is approximated as 655 kg./m^3 of pile above the potato (Muthukumarappan, et al. 1994). The development of pressure flattening is often proposed to result from the interaction of three factors; pressure within the pile, duration of storage, and tuber moisture loss (Muthukumarappan, et al. 1994). Three different sets of experiments and analysis were conducted to attempt to determine 1) if there is a consistent pattern of cultivar differences in pressure flattening susceptibility from year to year, 2) if the use of late growing season applications of boron, calcium, and potassium reduced pressure flattening development, and 3) if additional applications of nitrogen near the end of the growing season reduced tuber physical maturity and/or increased pressure flattening development during storage.

Effect of Cultivar in Pressure Flattening Development.

At-harvest moisture loss increased the susceptibility to pressure flattening for some cultivars more than others (Castleberry and Jayanty, 2012). The significant differences between cultivars in the effects of moisture loss on pressure flattening development suggests that moisture loss (as a component of weight loss) may result in an increase in pressure flattening for some cultivars. However, cultivar specific physiological and anatomical features, such as those responsible for differences in blackspot bruise susceptibility may explain pressure flattening differences that are not directly related to tuber dehydration (Thornton and Bohl 1998; Corsini et al. 1999). Studies of russet cultivars have shown that mechanical resistance of tuber tissue samples can be affected by turgidity but the degree of turgidity loss that leads to tissue structural failure under pressure is likely cultivar specific (Bajema, et al. 1998). Tuber anatomical features such as cell size, cell wall thickness, and skin thickness may also contribute to the mechanical properties of the tissue and are different for different cultivars (Konstankiewicz and Zdunek 2001; Zdunek and Umeda. 2005). When plant tissue is compressed, the main effect is on the cell walls, which comprise the basic structural elements responsible for structural integrity of the tissue. Higher resistance to mechanical stress is found in smaller-sized cells but these cells may be less resistant to micro-damage (Konstankiewicz and Zdunek 2001; Zdunek and Umeda. 2005). Some cultivars may pressure flatten earlier than other cultivars even if the later flattening cultivars had higher initial rates of moisture loss (Castleberry and Jayanty, 2012). Five cultivars that had been planted between 2009 and 2012 at a farm and storage operated by a private company were evaluated for relative pressure flattening development. Asterix, Innovator,Russet Norkotah, Satina , and Yukon Gold were the cultivars evaluated because they included two russet cultivars, (Innovator and Russet Norkotah) and three specialty cultivars (Asterix, Satina, and Yukon Gold). It was also thought that Russet Norkotah, Satina, and Asterix would develop pressure flattening more slowly than Yukon Gold and Innovator based on the experience of the commercial storage operator.

Effect of Calcium, Boron, Potassium and Late Growing Season Nitrogen Applications on Pressure Flattening Development.

Calcium, boron, and potassium applications made late in the growing season were thought to improve tuber maturity or skin set. Calcium nutrition in particular was thought to be important for periderm development (Palta, 2010) Additionally, it was thought that the beneficial role of calcium in cell wall structure (Palta, 2010) may improve structural integrity of the cells and therefore confer increased resistance to pressure flattening. Furthermore, tuber concentrations of calcium have been reported to be affected by genetic factors that relate to cultivar differences (Brown et al. 2012). Previous research is unclear as to whether in-season applications of calcium affect yield, although there may be an improvement in cooked potato texture (Agblor and Scanlon, 2002). Boron is frequently applied to potato fields although yield and quality effects are uncertain even at higher application rates (Hopkins et al. 2010). Applications of potassium are reported to reduce specific gravity but also have an impact on yield (Panique et al.1997). Interactions between calcium, boron, and potassium applications have also been studied. Calcium and boron applications late in the season are believed to cause improve senescence and improve tuber maturity. However, boron at higher concentrations may interfere with calcium uptake (Abdulnour, et al.2000). Our initial field research in 2009-2010 included a field trial using Yukon Gold to evaluate late season applications of different rates of calcium, boron, and potassium and various combinations of these nutrients evaluated on subsequent pressure flattening development. In 2011 and 2012, research was focused on late growing season applications of the individual nutrients, as well as nitrogen, to russet cultivars to determine whether there was an effect on pressure flattening development.

Effect of Late Growing Season Nitrogen Applications

Previous research examining the relationship between storability, tuber maturity and nitrogen fertilization has focused on issues that are of great importance to potatoes grown for processing (Long et al. 2004). In the processing potato context, tuber immaturity would refer to low specific gravity or higher concentrations of reducing sugars, which are factors of great importance to potato processors (Labowski 2007). Increased nitrogen applications during the late part of the growing season can result in lower specific gravity and therefore reduce suitability for processing. The specific gravity and sugar content are not as important to fresh market potato growers in Colorado, who prioritize yield and appearance. For fresh market potato production immaturity of a potato crop would refer to poorly developed periderm or other factors. Yield effects of nitrogen rate and application timing are often cultivar dependent and differences have been observed among russet cultivars (Love et al. 2005). Some cultivars appear to do well with only pre-plant nitrogen applied, while others seem to respond to post emergence applications during the growing season (post-emergence). Although pre-plant nitrogen avoids some of the problems associated with later applications, there are environmental consequences to both excessive total nitrogen and early applications (Shrestha et al, 2010, and Millard 1990). Late season applications of nitrogen are often successful in controlling early blight (Soltanpour and Harrison, 1974), but some research indicates use of specific fungicides would provide control if late nitrogen applications are undesirable (Millerand Rosen 2005). Tuber moisture losses during storage are the direct cause of “shrink” losses during storage and have been observed as a consequence of excessive late season nitrogen (Kolbe et al. 1995). Furthermore, harvest of immature tubers or tubers with poor skin set can result in an increase in moisture loss (Thornton and Bohl,1998 and Olsen and Odberg, 2003) and therefore could potentially result in an increase in pressure flattening. The economic returns from fresh market potato crops are affected not only by conditions and diseases during the growing season, but also by factors occurring during harvest and storage. Increased nitrogen applied during the late growing season that results in tuber immaturity may delay harvesting risking frost damage in areas with short growing season. Potato growers and shippers who sell to the fresh market often have significant economic losses from harvest damage as well as from pressure flattening and moisture loss (shrinkage) in storage, possibly as a result of excessive nitrogen fertilization. Immature potato tubers are more prone to shrinkage of potatoes in storage, and more susceptible to bruising and other harvest damage (Thornton and Bohl, 1998, Baritelle et al. 2000). Increased periderm damage during harvest can result in an increase in moisture loss from the tubers of up to 1000 times that of a non-damaged, well suberized tuber (Olsen and Odberg, 2003). Additionally, tuber immaturity can delay or reduce wound healing or suberization of the crop during the early part of the storage season (Lulai and Orr, 1995). Tuber moisture loss can result in further economic losses due to increased susceptibility to pressure flattening of potatoes stored for the fresh market (Castleberry and Jayanty 2012). Research was undertaken in 2010 and 2011 to study the effects of different rates of late growing season nitrogen on harvest damage, and pressure flattening of several popular russet potato cultivars. An additional trial in 2011included an organic nitrogen source applied three weeks earlier than the inorganic source.

Materials and Methods

Cultivar Susceptibility Methodology

The 2009- 2010 evaluation of cultivar differences and pressure flattening development used three, approximately 10 kg. potato samples that were dug by hand from a field of each cultivar on the day of commercial field harvest. The filled sacks were then stored inside a climate controlled corridor at approximately 14 degrees C and 95% relative humidity while samples from the other fields were obtained during the next few days. Once the at-harvest samples were all collected they were tied shut using 1.3 cm diameter polymer rope and taken to a 30,000 cwt. storage bin that was being filled. The operator of the piling apparatus created a flat pile of potatoes with an area approximately 1 m. high and 3.7 m. by 1.2 m.

wide in the middle of the storage cellar. The sample bags were laid flat on top of this short potato pile in a randomized fashion. Additional polymer rope was then used to tie the bags closely together by threading the rope through one end and sliding them together one at a time. The excess rope that was still attached to the samples was then tied to the metal railing of a catwalk above the pile. The piling line operator then resumed filling the storage bin until it was uniformly filled to a height of 5 m. Once the bin was unloaded, samples were retrieved, and tubers were removed from the bags to be evaluated for pressure flattening. Unfortunately, the tubers were only stored for 4 months prior to bin unloading and samples from the cultivar Innovator had sufficient damage and disease that they were not able to be evaluated properly.

For the cultivar susceptibility data presented from 2011 and 2012, 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 degrees 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 to be 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. In 2012, the thirty tuber samples were collected from the commercial storages one week after harvest. The texture analyzer, or instrumented penetrometer, used to determine peak load required for surface tissue deformation was a 10 kg. capacity Brookfield CT3 Texture Analyzer 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 3mm. target deformation depth was thought to 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., from this point on the instrument recorded the force applied every one hundredth of a second. This continued until the probe was 3mm. below the 75 gram "trigger" setting. Once 3mm.deformation was 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.

Calcium, Boron, and Potassium Research Methodology

For the first year of research, in which combinations of boron, calcium, and potassium were applied to field plots of the cultivar Yukon Gold, research plots were established in a commercially planted field managed by a cooperating farm. The plants were established during commercial planting and then subdivided into plots following emergence. Approximately 135 kg. per hectare nitrogen (a 32-0-0 liquid formulation) was applied to the field (78 kg. at planting with an additional 3 applications of 22 kg. incrementally until 60 days after planting). Plots were established in a randomized block design, with each combination of treatments replicated four times. Each individual plot was three rows (planted on .9 m. centers) by 5 m. with a 1 m. plant-free border between the ends of the plots. Each plot had a 50 cm. long wooden stake that was labeled with treatment code to make nutrient applications more efficient and accurate. Each plot was treated with the desired nutrient rate and combination dissolved into 2 l. of water and then applied with a 3.3 l. hand sprayer to the soil along the upper sides of the raised rows, rather than sprayed on the foliage. Boron applied was Solubor, a 20% boron compound that is soluble in water. Potassium was applied as potassium chloride (KCl) dissolved in water at the desired rate of potassium. Calcium applied was calcium chloride ($CaCl_2$), again dissolved in water to obtain the desired concentration. Control plots and plots that did not include a second nutrient were sprayed with water.

Treatments were made a few hours before the irrigation system applied 1.2 cm of water. Boron, calcium, and potassium were applied at 75 days after planting in the following combinations in which control is no application of the nutrient:

1. Calcium at control, 11.1 kg./hectare additional, and 22.5 kg./hectare additional X potassium at control, 2.7 kg./hectare additional, 5.7 kg./hectare additional, and 11.1 kg./hectare additional.
2. Calcium at control, 11.1 kg./hectare additional, and 22.5 kg./hectare additional X boron at control, .6 kg./hectare additional, 1.2 kg./hectare additional, and 2.2 kg./hectare additional.
3. Potassium at control, 2.7 kg./hectare additional, 5.7 kg./hectare additional, and 11.1 kg./hectare additional X boron at control,.6 kg./hectare additional, 1.2 kg./hectare additional, and 2.2 kg./hectare additional.

At harvest, yield was evaluated for the center row of each three row plot and 50 tubers from each treatment combination were placed in the experimental ventilated container design and evaluated for pressure flattening after 5 months storage duration.

The boron, calcium and potassium trials established in 2011 were much simpler. Research plot trials were established at the San Luis Valley Research Center of the Colorado State University system, using two russet skin cultivars, Russet Norkotah Selection 8 and Classic Russet, planted as separate experiments. The experimental design used was a randomized block design to attempt to minimize field location effects on yield. Each treatment was replicated three times. Each plot consisted of three 5 m. rows planted on 0.95 m. centers. Plots were separated at the ends by a 1 m. long plant free area. The research plots were fertilized with 67 kg. per hectare of nitrogen (a 32-0-0 liquid fertilizer) applied at planting and three additional applications of about 22 kg. each were made during June and early July. Treatment applications were made at 90 days after planting. The nutrient applications applied to each cultivar consisted of a control (water), boron (solubor w/ 20% boron) at 2.2 kg./hectare, calcium ($CaCl_2$) at 22.5

kg./hectare, nitrogen (32-0-0 liquid) at 22.5 kg./hectare, and potassium (KCl) at 11.1 kg./hectare. After diluting or mixing with water, each treatment was applied using a hand sprayer at a final volume of 3.3 l. per plot. Application was directed towards the upper portion of each raised row, rather than being applied to the foliage. Plots were harvested 3 weeks after defoliation of the crop. At harvest, yield data was not collected and tubers from the plots of the same cultivar and treatment were mixed. For each cultivar, seventy tubers from each treatment were then selected and placed into fourteen 2 kg. capacity plastic mesh bags, weighed on an analytical balance, and labeled. These samples would be used for pressure flattening evaluation using the ventilated container system. Seven bags, serving as replicates, were placed in one ventilated container to be unloaded after 3 months storage duration, and the second set of seven bags was placed in a second ventilated container to be unloaded after six months storage duration. At the time of unloading samples would be evaluated for pressure flattening.

Late Growing Season Nitrogen Application Methodology

Research plot trials were established at the San Luis Valley Research Center of the Colorado State University system in 2010 and 2011 to evaluate the effect of late growing season nitrogen applications on pressure flattening development. The experimental design used was a randomized block design to attempt to minimize field location effects on yield. Individual plots consisted of three, 6 m. rows and each treatment was replicated 4 times. The standard practice for both years was to apply sixty seven kg. per hectare of nitrogen applied at planting and three additional applications of about 22 kg. per hectare each were made during June and Early July. All treatment applications of conventional nitrogen were done using a 32-0-0 liquid nitrogen fertilizer. The organic nitrogen source applied in July as part of the 2011 research plot trials was a dried animal blood product “bloodmeal” which corresponded to an 11-0-0 nitrogen fertilizer.

For the first field research year, research plot trials were established for four russet cultivars: Canela Russet, Centennial Russet, Rio Grande Russet, and Russet Norkotah Selection 8. Plots were planted on May 6th, 2010 and late applied nitrogen treatments (control, additional 22.5 kg./hectare nitrogen, and additional 45 kg./hectare nitrogen) were applied as a liquid foliar application to the upper portion of the raised row, rather than over the foliage, on August 10, which was approximately 90 days after planting. Control plots were sprayed with water. This was approximately 25 days prior to vine desiccation. Research plots were mechanically harvested on September 28th and October 2nd. Tubers from each plot were weighed to determine yield and were evaluated for harvest damage such as skin peeling, and shatter bruise. Subsamples were also created following grading to be tested for tuber skin resistance to shearing force, specific gravity, and moisture loss from 24 hours in a drying oven at 37 degrees C. After yield was measured, fourteen subsamples were created for each cultivar and treatment using 2 kg. plastic mesh bags. These samples, each consisting of five tubers would be used to measure long-term moisture loss and for pressure flattening evaluation after storage. Seven samples (replicates) of each treatment and cultivar were placed in each of two ventilated containers as part of an experimental design for inducing pressure flattening. After 3 months of storage for one container, and again after 6 months of storage in the other container, the subsamples of tubers were removed, weighed again, and observed for the number and diameter of pressure flattened areas.

In 2011, replicated, randomized block design plot trials were established, managed, and harvested similar to the 2010 field experiments. In 2011, one set of experiments evaluated the cultivars Canela Russet, Mesa Russet, Classic Russet, Rio Grande Russet, and Russet Norkotah Selection 8 with a non-treated control, 22.5 kg. per hectare additional nitrogen, and 45 kg. per hectare additional nitrogen applied 90 days after planting. Once again, the application was made to the upper portion of the raised row, rather than over the foliage. Each cultivar was planted and analyzed separately. A second set of experiments using the cultivars Canela Russet, Centennial, Premier, and Rio Grande Russet was evaluated for the effects of a non-treated control, 22.5 kg./hectare additional organic source nitrogen, 45 kg./hectare additional organic source nitrogen, 22.5 kg./hectare additional inorganic source nitrogen, and 45 kg./hectare additional inorganic source nitrogen. The organic nitrogen source was applied as a dry fertilizer which spread over the ground for the appropriate plots at 70 days after planting. The inorganic nitrogen was applied at 90 days after planting. For this second trial, nitrogen applications were made using a calibrated 3 row sprayer that applied the nitrogen over the tops of the plants, including the foliage. Plots were harvested 3 weeks after defoliation of the crop. Yield and relevant at-harvest tests including specific gravity were conducted. After yield was measured, fourteen subsamples were created for each cultivar and treatment using 2kg. plastic mesh bags. These samples, each consisting of five tubers would be used to measure long-term moisture loss and for pressure flattening evaluation after storage. Seven samples (replicates) of each treatment and cultivar were placed in each of two ventilated containers as part of an experimental design for inducing pressure flattening. After 3 months of storage for one container, and again after 6 months of storage in the other container, the subsamples of tubers were removed, weighed again, and observed for the number and diameter of pressure flattened areas.

Evaluation of the Samples for Pressure Flattening

Pressure flattening was evaluated for each tuber within each sample bag. Tubers were visually inspected and each flattened area was circled, numbered in ascending order using permanent markers, and its diameter was measured. Counting the number and measuring the individual diameter of each bruised area enabled estimation of the USDA quality grade for each tuber in each bag. For example, USDA potato grade standards specify that a 227-340g tuber which has more than 18 cm^2 combined flattened area is beyond the grade tolerances established for a US No. 1 or US No. 2 potato. The samples evaluated in 2009-2010 were recorded as the percentage of tubers that had no observable pressure flattening, the percentage that had pressure flattening but were still acceptable as a US No. 1 potato, and the percentage of tubers that had pressure flattening that would reduce the quality of the potato to a US No. 2 or below. In 2010 and 2011, individual flattened areas were measured and averaged for each sample bag, with the number of bags serving as a replicate. Pressure flattening from those experiments is typically presented as the averaged pressure flattened area per tuber in cm^2.

Statistical Analysis and Design

Field trials such as those designed to test applications of nitrogen or other nutrients were planted in a randomized block design with the blocks of treatments arranged based on distance along the length of the irrigation system. This was intended to prevent a damaged or plugged spray nozzle on the irrigation system from affecting more than one replication of each treatment. The plot designs did not include different cultivars within the same plot, so each cultivar was planted as a separate plot trial. Tubers that were tested or subjected to pressure flattening were randomly selected from among 227-340g. 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 α=0.05 using the data analysis toolpak in Microsoft Excel 2007. Data for individual tubers was averaged within each sample bag, with the bag average being used as a replicate. Decayed, diseased, or broken tubers were discarded and the average for each bag did not include these tubers. Error bars in figures and means separation in tables using letter based groupings are based on a calculated Fishers LSD at α=0.05 using the standard error and an approximated T-value of 2.

Results

Cultivar Susceptibility Results

Although it was not possible to evaluate the pressure flattening of the Innovator samples, there were fewer tubers with “scorable” pressure flattening following 4 months storage for Asterix andRusset Norkotah, relative to Yukon Gold (3.2% and 3.32% compared to 9.87%) (Figure 32).

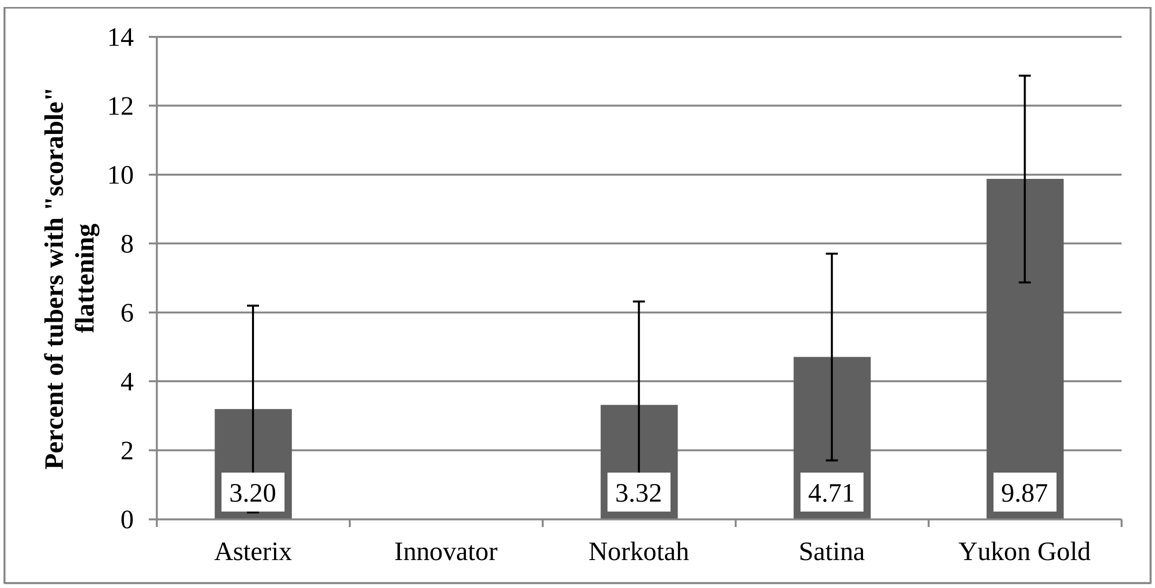

Figure 32. Percent of tubers with pressure flattening that is sufficient to reduce quality grade below US No.1 (scorable) for samples of different cultivars removed after 4 months in commercial storage (2009-2010).

When the peak load required for 3mm surface deformation was evaluated for the different cultivars in 2011, Asterix, Russet Norkotah, and Satina all were significantly higher than Innovator or Yukon Gold (Figure 33). Similarly, after 6 months storage duration in the ventilated container system, Yukon Gold and Innovator produced significantly more pressure flattening per tuber in 2011 (Figure 34). The pressure flattened area was more than double for Innovator relative to Asterix, Russet Norkotah, and Satina cultivars.

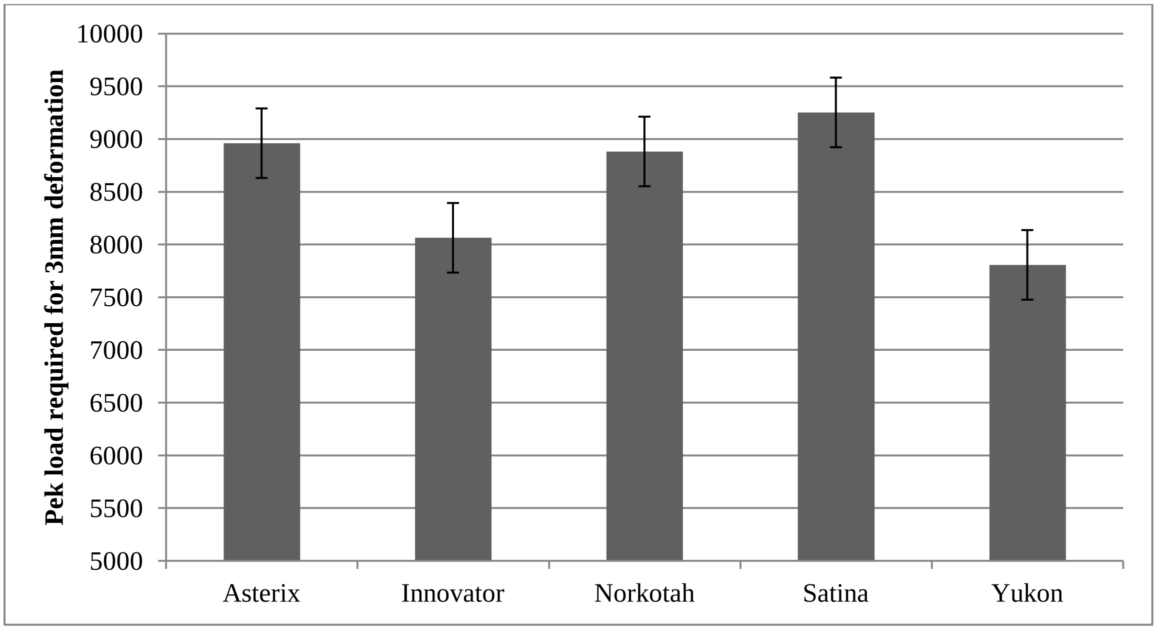

Figure 33. Peak load required for 3mm. surface deformation for samples from different cultivars after 1 month storage duration. (2011 data)

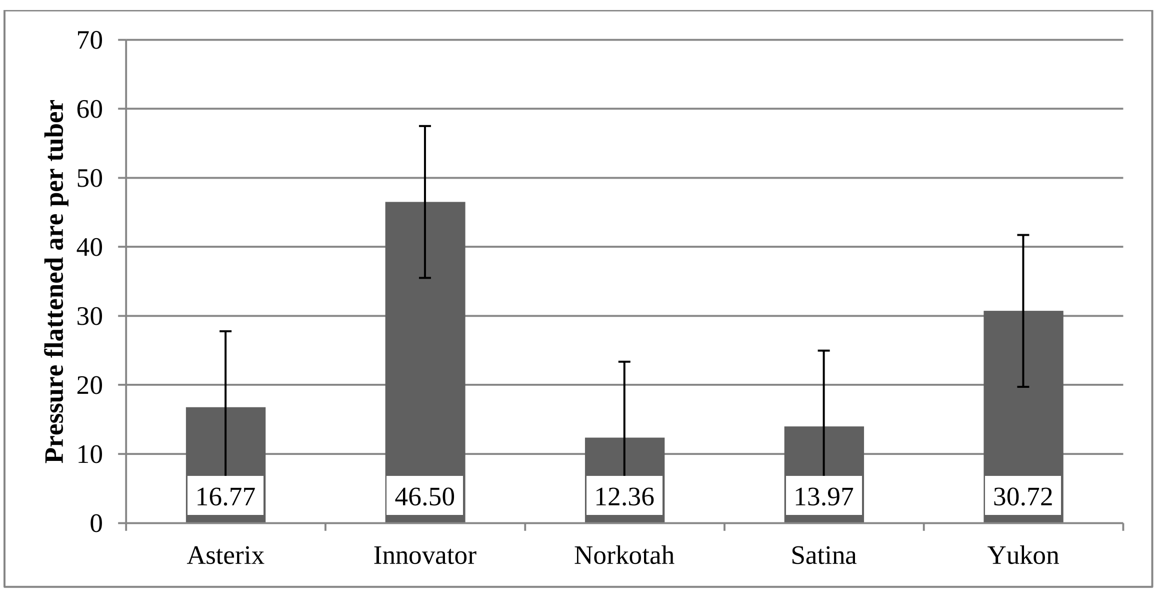

Figure 34. Pressure flattened area per tuber (cm^2) for different cultivars after 6 months storage duration 2011-2012 data.

A similar trend was observed when texture analysis and pressure flattening measurements were conducted in 2012-2013. The peak loads required for 3mm. deformation were significantly higher for Russet Norkotah, Satina and Asterix compared to Innovator and Yukon Gold (Figure 35). Data obtained after 3 months storage from the 2012-2013 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 (Figure 36). 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. Results from the 6 month storage duration are likely to be more dramatic.

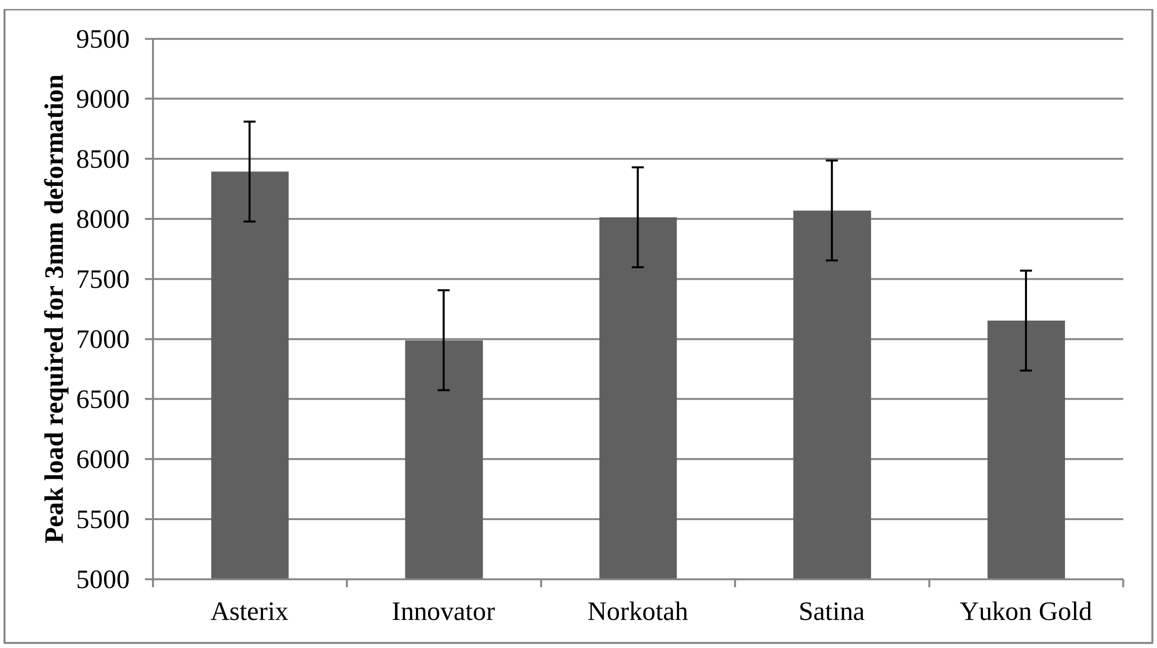

Figure 35. Peak load required for at-harvest 3mm. surface deformation for samples from different cultivars (2012 data)

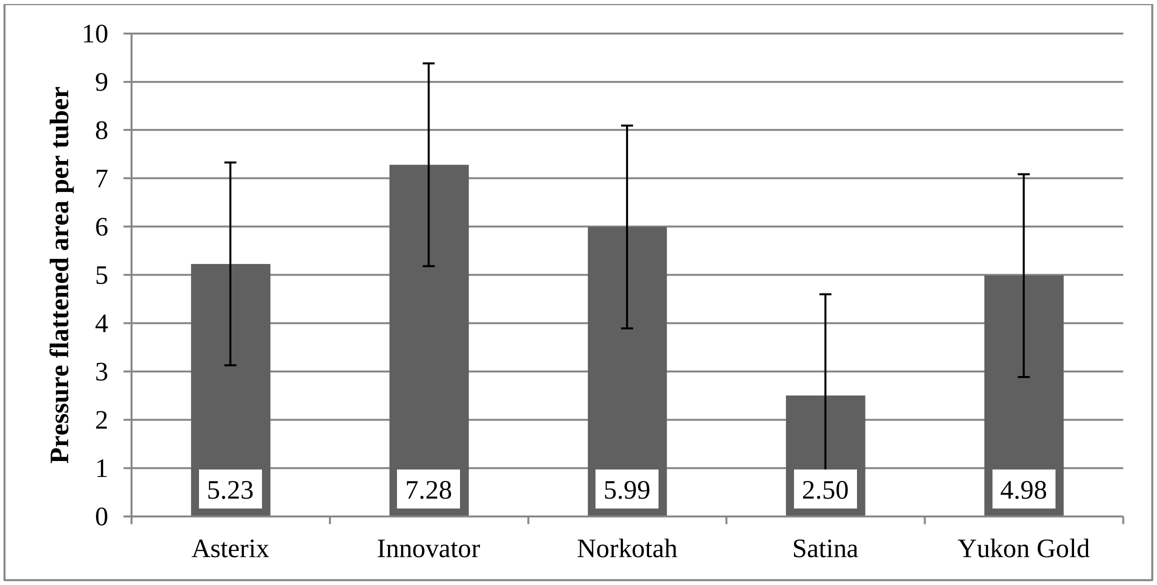

Figure 36. Pressure flattened area per tuber (cm^2) by cultivar after 3 month storage duration (2012-2013 data).

Nutrient and Nitrogen Fertility Application Results

Results from the first calcium, potassium, and boron trial produced no significant differences in either percent of tubers with scorable pressure flattening or incidence of non-scorable pressure flattening (Table 4). There may be a slight trend towards increased pressure flattening for treatments without calcium or potassium but included variable rates of boron. When soil tests were taken post harvest, the results revealed that the plot area already had high concentrations of boron and calcium in the soil.

Table 4. Comparison of applications of Calcium, Boron, and Potassium based on percentage of tubers with pressure flattening exceeding the area allowed by the USDA grade and quality standards for US. No. 1 potatoes and percentage of tubers with any pressure flattening.

% Scorable Damage	**No Calcium**	**11.2 kg/ha Calcium**	**22.5 kg/ha Calcium**	
No Boron	12	8	18	
Boron .56 kg/ha	22	9	2	
Boron 1.1 kg/ha	4	15	11	
Boron 2.2 kg/ha	10	9	7	
No Potassium	17	9	13	
Potassium 2.8 kg/ha	13	8	11	
Potassium 5.6 kg/ha	7	11	9	
Potassium 11.2 kg/ha	10	14	5	
% Scorable Damage	**No Potassium**	**2.8 kg/ha Potassium**	**5.6 kg/ha Potassium**	**11.2 kg/ha Potassium**
No Boron	10	17	14	8
Boron .56 kg/ha	17	6	13	7
Boron 1.1 kg/ha	13	7	5	16
Boron 2.2 kg/ha	12	13	3	8
	\			
% Any Flattening	**No Calcium**	**11.2 kg/ha Calcium**	**22.5 kg/ha Calcium**	
No Potassium	56	71	81	
Potassium 2.8 kg/ha	75	81	70	
Potassium 5.6 kg/ha	62	77	62	
Potassium 11.2 kg/ha	69	67	63	
No Boron	68	81	75	
Boron .56 kg/ha	65	82	73	
Boron 1.1 kg/ha	57	68	64	
Boron 2.2 kg/ha	73	69	64	
% Any Flattening	**No Potassium**	**2.8 kg/ha potassium**	**5.6 kg/ha Potassium**	**11.2 kg/ha Potassium**
No Boron	71	74	79	72
Boron .56 kg/ha	70	78	76	69
Boron 1.1 kg/ha	61	72	50	70
Boron 2.2 kg/ha	77	77	64	54

There were no statistically significant differences in pressure flattened area per tuber for the 2011-2012 experiments as well (Table 5). The cultivar Russet Norkotah may have shown some trend towards reduced pressure flattening for the treatment using the 22.5 kg. per hectare calcium after 6 months storage and the cultivar Classic Russet may have shown a trend for additional early pressure flattening development after application of 2.2 kg. per hectare additional boron (Figure 37 and Figure 38).

Table 5. Pressure flattened area per tuber (cm^2) by cultivar by late season fertilizer application after 3 and 6 months storage duration (2011-2012 data)

Cultivar	Treatment	3 month storage	6 month storage
Classic Russet	Control	8.7 NS	19.0 NS
	Boron 2.2 kg. hectare	15.7 NS	16.5 NS
	Calcium 22.5 kg./hectare	6.2 NS	16.2 NS
	Nitrogen 22.5 kg./hectare	4.3 NS	18.1 NS
	Potassium 11 kg./hectare	7.4 NS	16.3 NS
Russet Norkotah	Control	3.3 NS	20.8 NS
	Boron 2.2 kg./hectare	6.3 NS	16.3 NS
	Calcium 22.5 kg./hectare	5.0 NS	10.1 NS
	Nitrogen 22.5 kg./hectare	6.5 NS	18.6 NS
	Potassium 11 kg./hectare	5.4 NS	15.4 NS

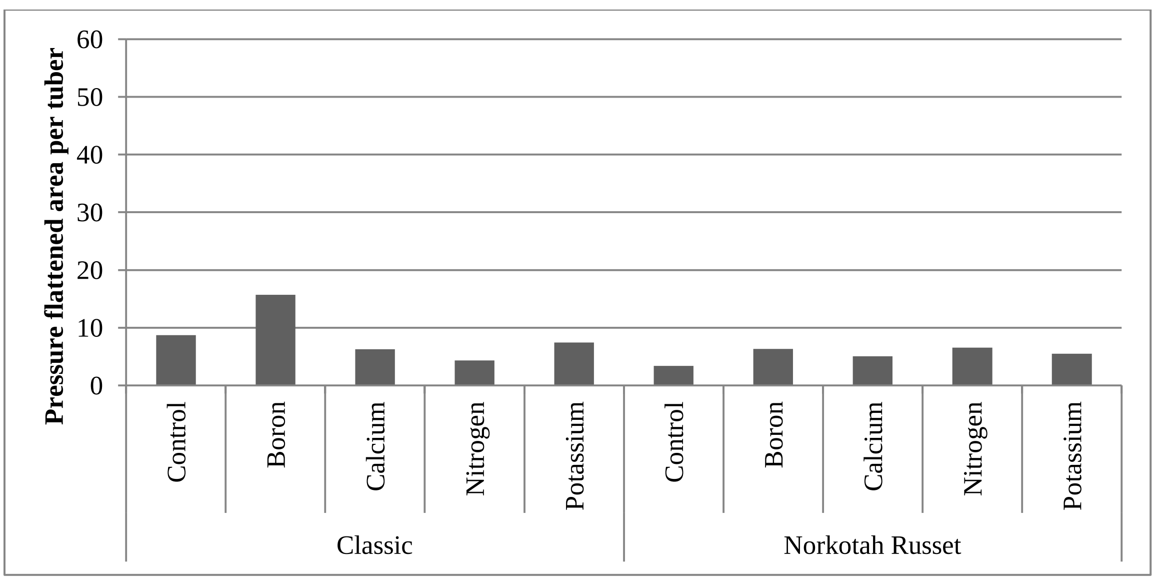

Figure 37. Pressure flattened area per tuber (cm^2) after 3 months storage duration for 2011-2012 late season fertilizer trials.

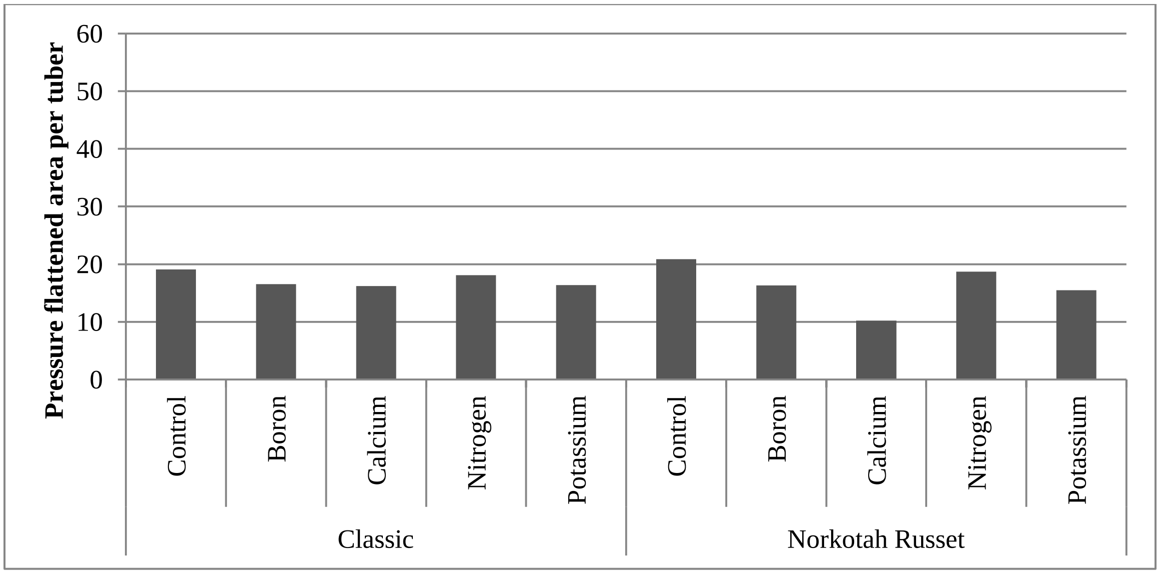

Figure 38. Pressure flattened area per tuber (cm^2) after 6 months storage duration for 2011-2012 late season fertilizer trials

The soil at the San Luis Valley Research Center (classified as a loamy-skeletal, mixed (calcareous) frigid Aquic Ustorthents) includes many rocks that are 170-284 g. and many rough-surfaced and jagged rocks. As a result, very high percentages of at harvest skin damage were observed. A typical farm would not usually experience as much damage as was observed in this study. In 2010, there was a trend towards increased skin removal and damage of tubers at harvest across all cultivars as a result of additional late season nitrogen, although the numbers were not statistically significant (Figure 39).

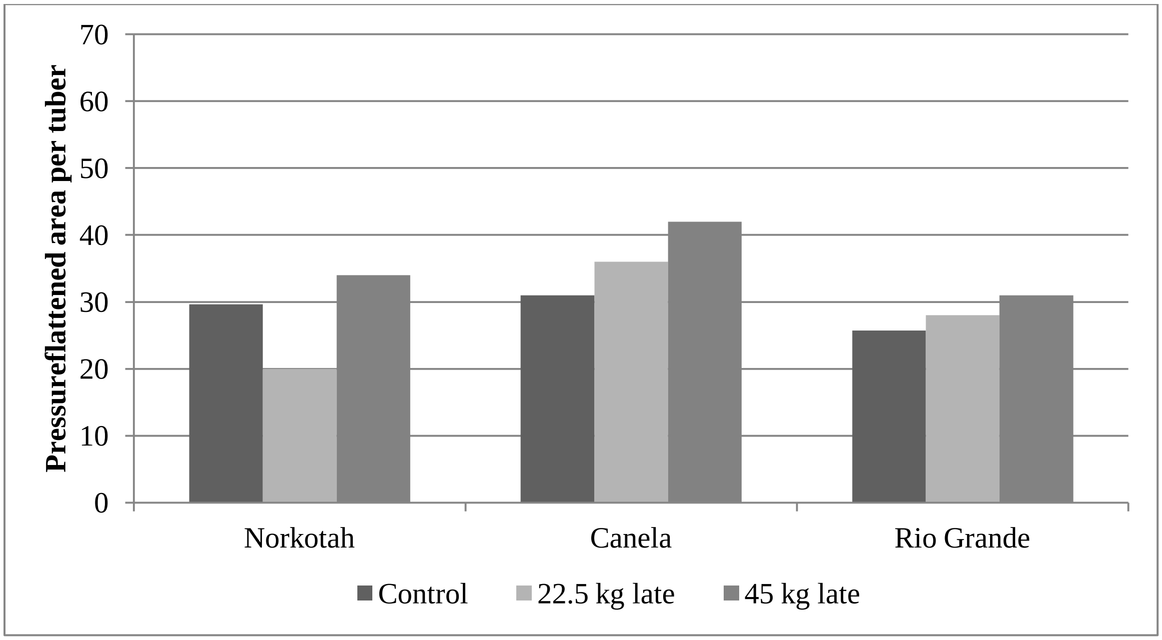

Figure 39. 2010 Percent of tubers with at-harvest skinning or damage by cultivar and late season fertility treatment.

Results from 2011 were less consistent (Figure 40), with trends for Canela Russet indicating increased damage with additional nitrogen but results for Rio Grande russet indicating an opposite trend. Because of the very wide variability in damage results it was difficult to determine whether results were due to late nitrogen application rates or simply variability in the amount or large rock that made it into the harvester with the potatoes. No observed differences in either 2010 or 2011 were statistically significant.

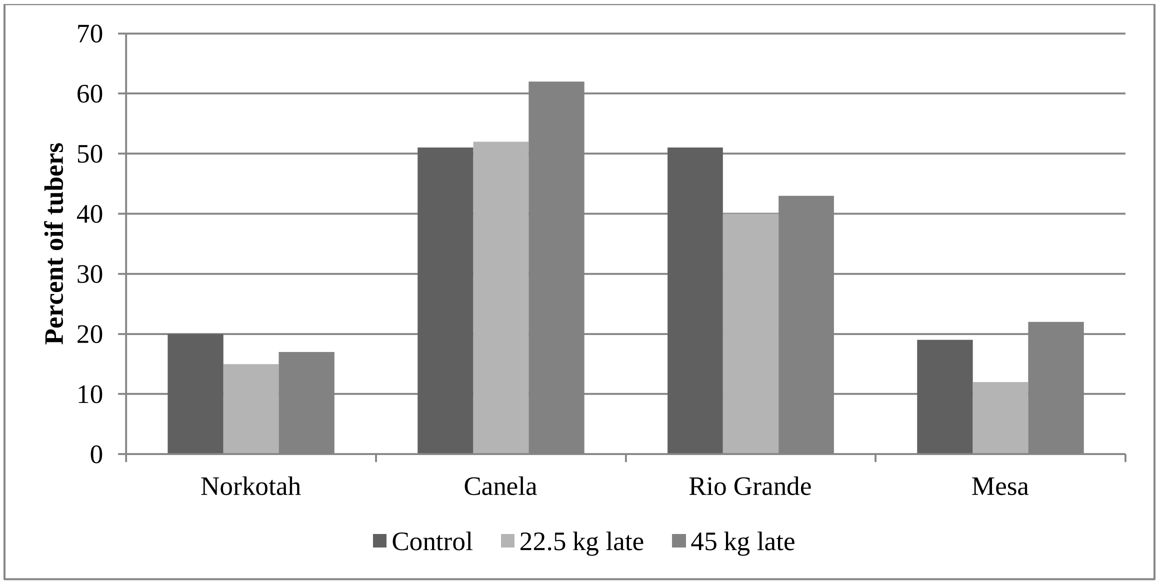

Figure 40. 2011 Percent of Tubers with At-harvest Skinning or Damage by Cultivar and Late Season Fertility Treatment.

A modified torqueometer designed to measure shear force resistance of skin was also used to evaluate the effect of late nitrogen applications on resistance to skin removal (Figure 41). The higher values indicate increased resistance and therefore more durable and more matured potato skin. A value of 3 or so would indicate moderate or susceptibility to skin damage, while 4 and above would indicate very mature and durable skin. There were no statistically significant differences (or strong trends) within each cultivar as a result of late nitrogen treatment.

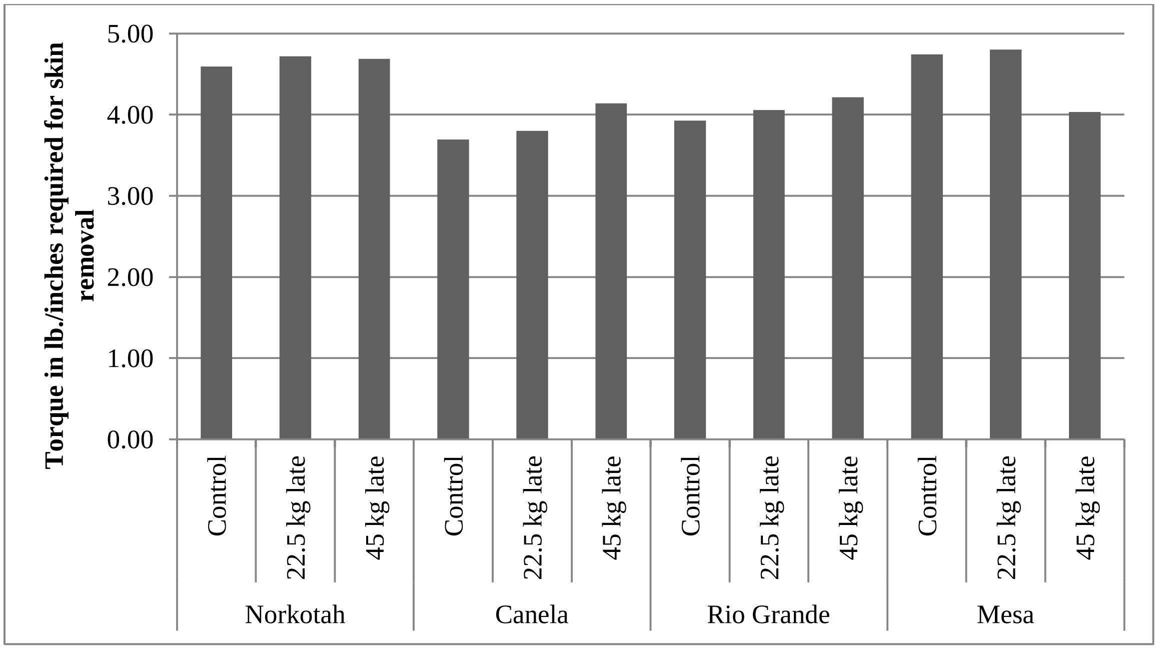

Figure 41. Resistance to Skin Shearing by Cultivar and Late Season Fertility Treatment for 2011.

Tuber specific gravity, which can also provide an indication of tuber maturity was tested at harvest. In general, higher specific gravities indicate more crop maturity within a specific cultivar. The 2010 results were varied across the cultivars, with higher specific gravities observed for the 22.5 kg. per hectare nitrogen treatment for Russet Norkotah CO8 and Canela Russet, while there was a trend towards decreased specific gravity with additional nitrogen for Rio Grande Russet (Figure 42).

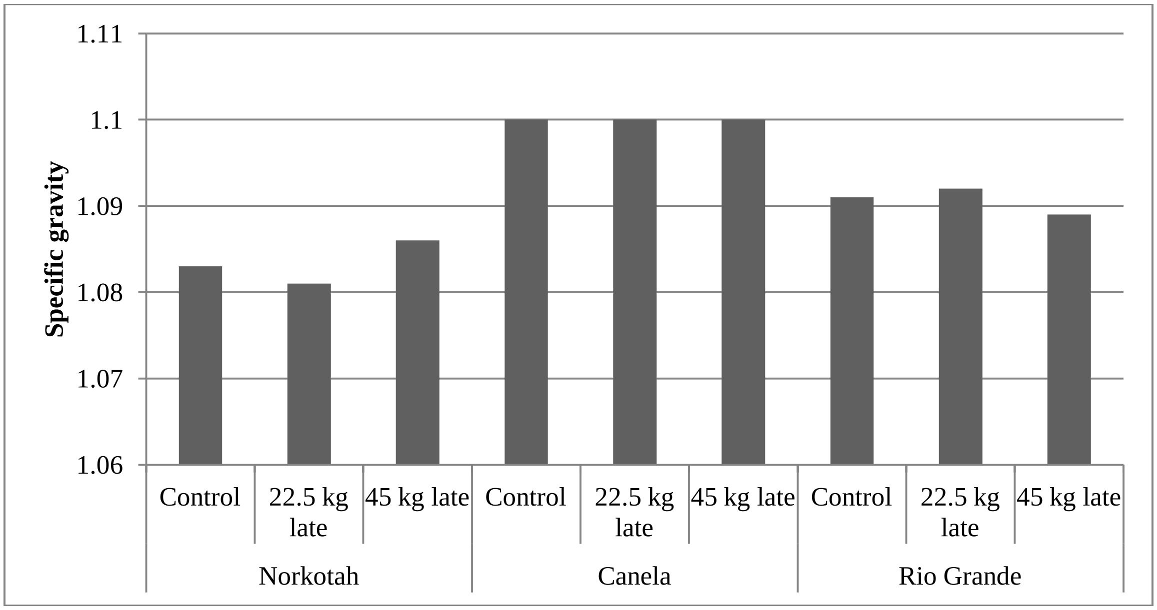

Figure 42. Tuber specific gravity for each cultivar by late nitrogen application treatment (2010 data).

Specific gravities in 2011 showed an expected trend across cultivars of decreasing specific gravities as a result of additional late season nitrogen fertilization (Figure 43).

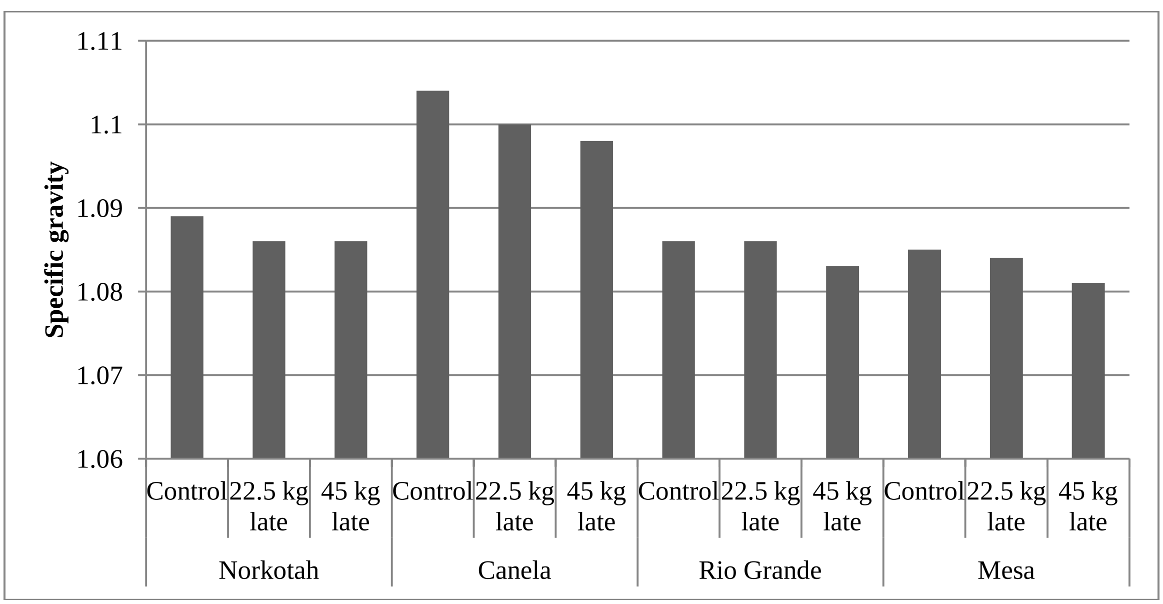

Figure 43. Tuber specific gravity for each cultivar by late nitrogen application treatment (2011 data).

An important part of the research program was to evaluate if there were storage problems that result from late season nitrogen. There were no observed differences in tuber moisture loss (shrink) during storage (data not shown). Data from 2010-2011 indicate significant differences in pressure flattening following different storage durations in the ventilated container system (Table 7). At 3 month storage duration Canela Russet treated with 45 kg. per hectare additional nitrogen produced significantly more pressure flattened area per tuber compared with the control treatment (32.6 cm^2 vs. 18.4 cm^2) (Figure 44) However the opposite was true of the samples recovered after 6 months storage, in which the Canela Russet treated with 45 kg. per hectare additional nitrogen showed a trend towards less pressure flattening. There were significant increases in the pressure flattened area per tuber for Rio Grande and Russet Norkotah that were treated with 22.5 kg. per hectare additional nitrogen, but oddly not significant increases for the potatoes treated with 45 kg per hectare additional nitrogen (Table 6 and Figure 45).

Table 6. Flattened area per tuber (cm^2) for each cultivar by late nitrogen treatment after 3 and 6 month storage duration (2010-2011 data).

Cultivar	Treatment	3 month storage	6 month storage
Canela Russet	Control	18.4 A	42.2 NS
	22.5 kg./hectare Late	24.3 AB	38.8 NS
	45 kg./hectare Late	32.6 B	32 NS
Centennial Russet	Control	28.8 NS	42.2 NS
	22.5 kg./hectare Late	38.6 NS	38.8 NS
	45 kg./hectare Late	32.2 NS	35.2 NS
Rio Grande Russet	Control	33.1 NS	35.5 A
	22.5 kg./hectare Late	32.0 NS	45.7 B
	45 kg./hectare Late	31.1 NS	35.9 A
Russet Norkotah	Control	22.4 NS	24.9 A
	22.5 kg./hectare Late	22.1 NS	38.8 B
	45 kg./hectare Late	18.5 NS	26.5 A

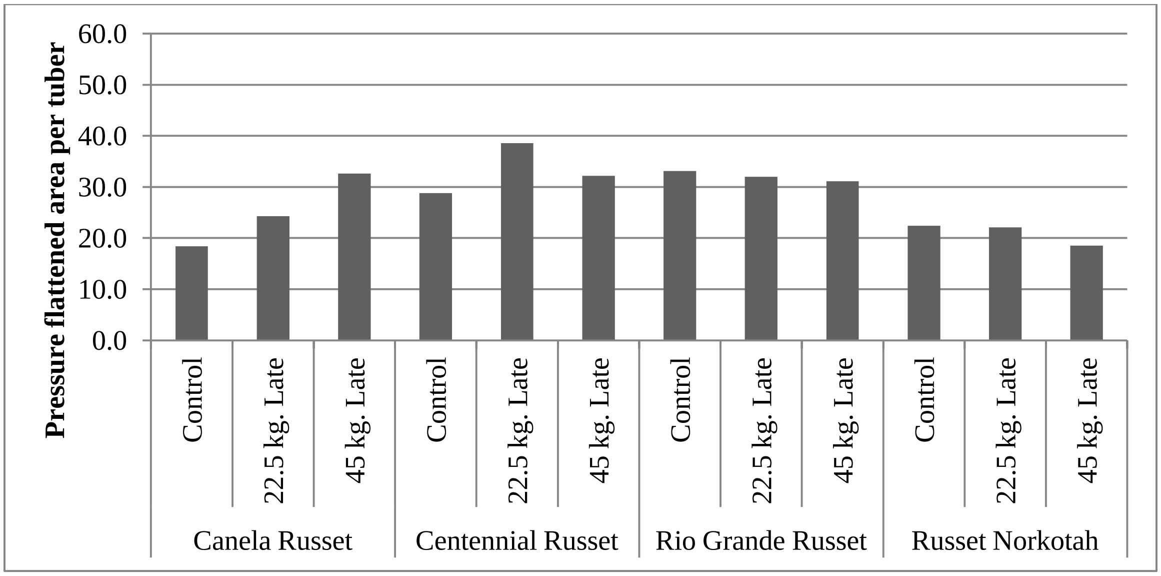

Figure 44. Pressure flattened area per tuber (cm^2) for each cultivar based on late nitrogen treatment after 3 month storage duration (2010-2011 data).

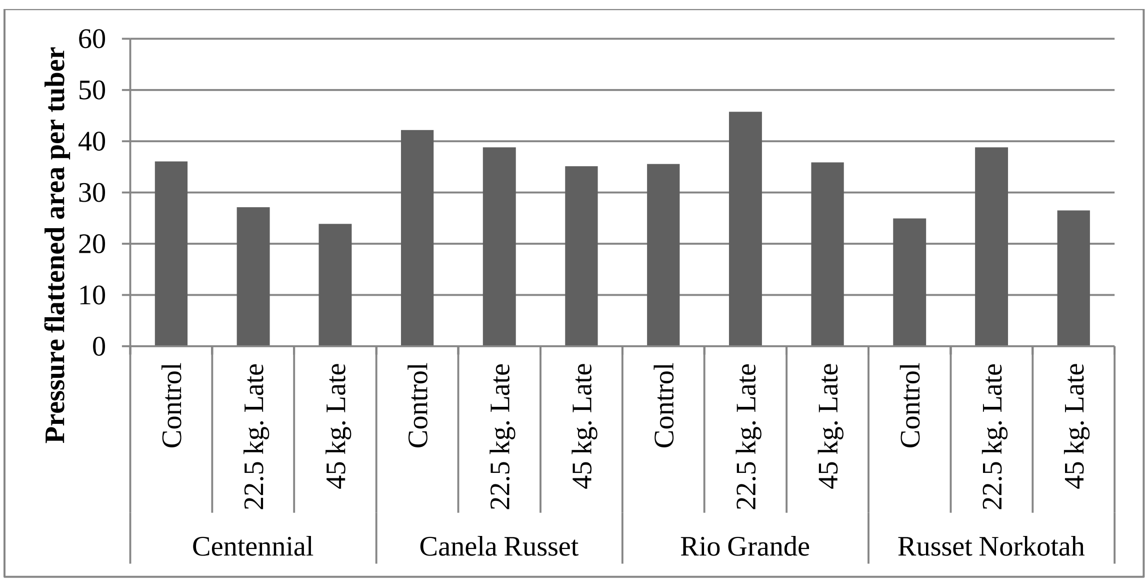

Figure 45. Pressure flattened area per tuber (cm^2) for each cultivar based on late nitrogen treatment after 6 month storage duration (2010-2011 data).

Pressure flattening results from 2011-2012 (Table 7, and Figure 46 and Figure 47) provided only one difference that was found to be statistically significant. Russet Norkotah that was provided the 22.5 kg. per hectare additional nitrogen treatment had more pressure flattened area per tuber compared to Russet Norkotah that received the 45 kg. per hectare additional nitrogen treatment. There was also a trend towards increased pressure flattening for the Canela that were treated with 22.5 kg. per hectare additional nitrogen after 6 months storage.

Table 7. Flattened area per tuber (cm^2) for each cultivar by late nitrogen treatment after 3 and 6 month storage duration (2011-2012 data).

Cultivar	Treatment	3 month storage	6 month storage
Canela	Control	23.2 NS	24.8 NS
	22.5 kg./hectare Late	22.0 NS	30.2 NS
	45 kg./hectare Late	11.7 NS	24.9 NS
Mesa Russet	Control	14.3 NS	18.7 NS
	22.5 kg./hectare Late	12.8 NS	19.5 NS
	45 kg./hectare Late	11.3 NS	15.6 NS
Russet Norkotah	Control	7.9 NS	17.9 AB
	22.5 kg./hectare Late	8.3 NS	19.0 B
	45 kg./hectare Late	10.2 NS	13.9 A
Rio Grande Russet	Control	17.3 NS	32.1 NS
	22.5 kg./hectare Late	13.0 NS	35.5 NS
	45 kg./hectare Late	13.6 NS	29.4 NS

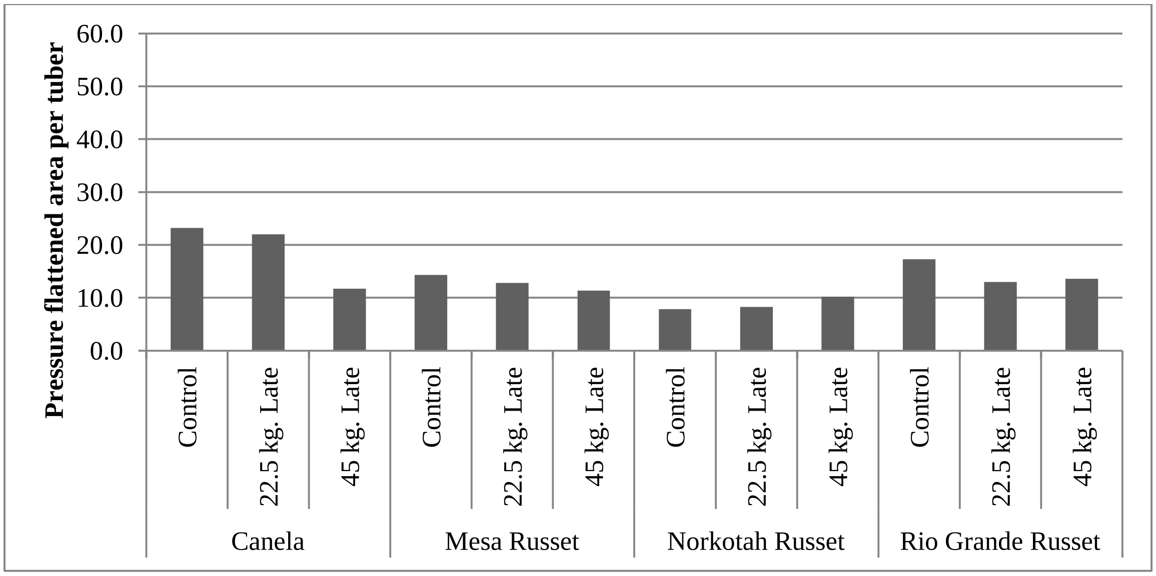

Figure 46. Pressure flattened area per tuber (cm^2) for each cultivar based on late nitrogen treatment after 3 month storage duration (2011-2012 data).

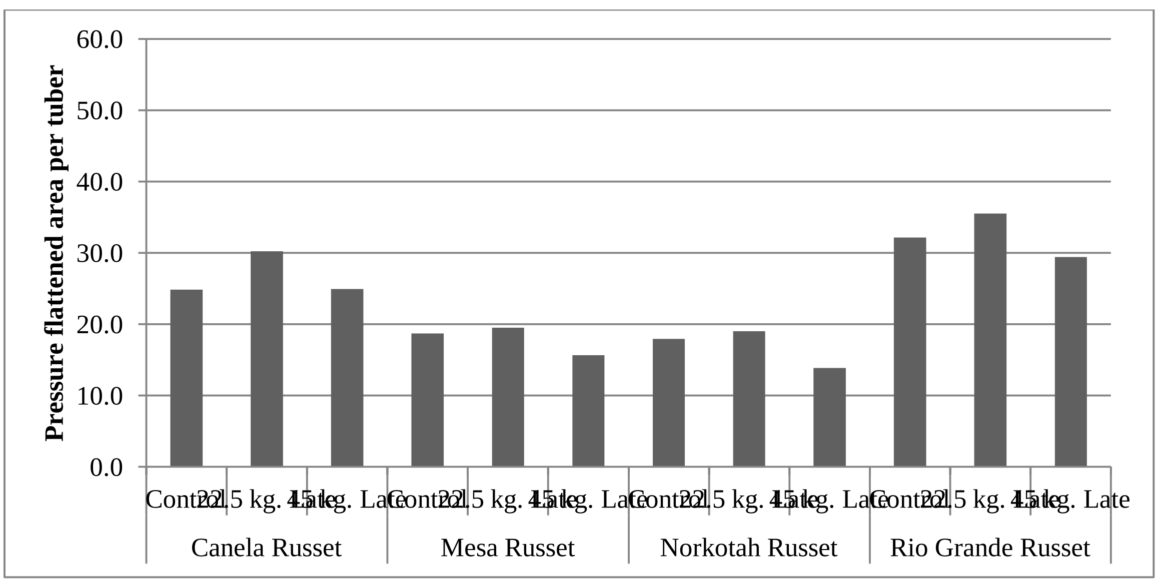

Figure 47. Pressure flattened area per tuber (cm^2) for each cultivar based on late nitrogen treatment after 6 month storage duration (2011-2012 data).

Table 8, and Figure 48 and Figure 49, present the pressure flattening results from the 2011 late nitrogen trial that included organic nitrogen sources and foliar application methodology. For Canela Russet, there was a statistically significant increase in pressure flattening after three months storage duration for the 45 kg. per hectare additional organic nitrogen treatment and a trend towards increased pressure flattening for the 45 kg. per hectare additional inorganic nitrogen treatment. Centennial pressure flattening results also showed a trend of increased pressure flattening for all additional nitrogen treatments after 3 months storage. After 6 months storage duration, there was a statistically significant increase in pressure flattened area for the 45 kg. per hectare additional organic nitrogen treatment compared to the control or the additional inorganic nitrogen applications. Additional inorganic nitrogen applied at 22.5 kg. per hectare and 45 kg. per hectare increased pressure flattening for Rio Grande relative to the control or the organic nitrogen applications.

Table 8. Flattened area per tuber (cm^2) for each cultivar by late nitrogen treatment after 3 and 6 month storage duration (2011-2012 data).

Cultivar	Treatment	3 month storage	6 Month Storage
Canela Russet	Control	13.2 A	34.3 A
	July +22.5 kg organic	16.8 A	31.1 A
	August +22.5 kg	17.1 A	36.8 AB
	July +45 kg organic	34.6 B	41.6 B
	August +45 kg.	26.5 AB	31.7 A
Centennial	Control	12.1 NS	33.5 NS
	July +22.5 kg organic	21.0 NS	33.9 NS
	August +22.5 kg	18.7 NS	36.7 NS
	August +45 kg	24.0 NS	37.6 NS
Premier Russet	Control	11.4 NS	35.9 NS
	July +22.5 kg organic	15.5 NS	34.9 NS
	August +22.5 kg	11.3 NS	33.1 NS
	July +45 kg organic	15.0 NS	32.0NS
	August +45 kg.	13.7 NS	
Rio Grande	Control	12.4 NS	30.3 A
	July +22.5 kg organic	10.3NS	33.6 AB
	August +22.5 kg	10.2 NS	42.8 C
	July +45 kg organic	12.7 NS	33.8 AB
	August +45 kg.	11.5 NS	41.8 BC

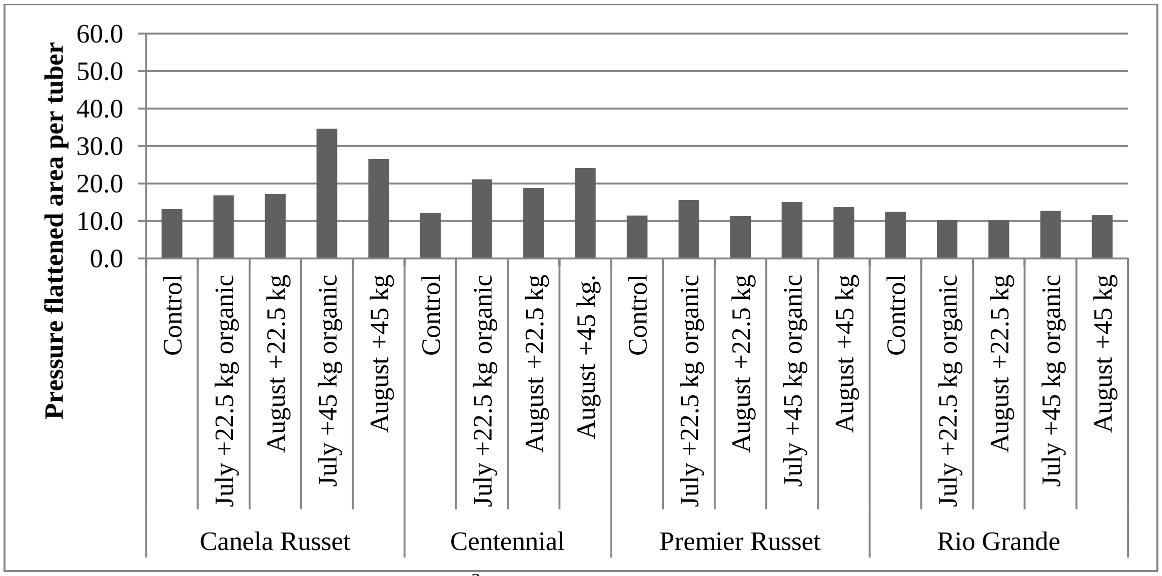

Figure 48. Pressure flattened area per tuber (cm^2) for each cultivar based on late nitrogen treatment after 3 month storage duration (2011-2012 data).

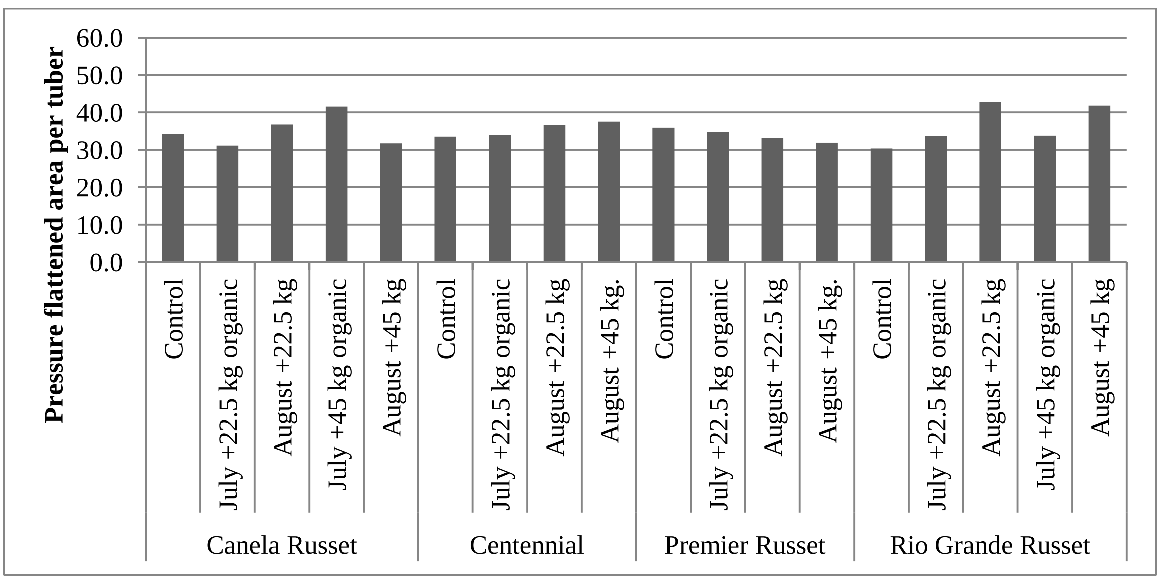

Figure 49. Pressure flattened area per tuber (cm^2) for each cultivar based on late nitrogen treatment after 6 month storage duration (2011-2012 data).

SECTION 4. EVALUATION OF POST-GROWING SEASON AND STORAGE METHODS TO REDUCE PRESSURE FLATTENING

Introduction:

Effect of Moisture Loss that Occurs Between Vine Dessication and the Initial Weeks of Storage

Pressure flattening occurs as the tuber surface becomes depressed or flattened due to constant contact with an adjacent tuber. This contacted area receives the force exerted by the adjacent tuber as a result of the weight of tubers above it in the pile, which increases as pile height increases. This pile pressure is approximated as 655 kg/m^3 of pile above the potato (Muthukumarappan, et al. 1994). The development of pressure flattening is often proposed to result from the interaction of three factors; pressure within the pile, duration of storage, and tuber moisture loss (Muthukumarappan, et al. 1994). Tuber moisture loss is regarded as an important factor in increasing the susceptibility of tissue to forming depressions and the extent of bruise in response to force (Kunkel and Gardner 1965; Hughes 1980; Lin and Pitt 1986; Muthukumarappan, et al. 1994; Konstankiewicz and Zdunek 2001; Olsen and Oberg 2003). As tuber moisture loss increases, cellular turgor decreases resulting in reduced mechanical resistance of the tissues. These tissues are more prone to changes in cell shape, cell wall cracking, debonding of the cells, and leakage of intracellular liquids through the cell walls (Konstankiewicz and Zdunek 2001). Reduced turgidity of the outer layers of tissue can cause increased susceptibility to pressure flattening, although excessive turgidity of tissue may also reduce resistance to deformation due to increased cell wall fracturing under pressure (Zdunek and Bednarczyk 2005). Dehydration and water loss from potato tubers occurs between vine kill and the final use by a consumer or processor. The tubers lose moisture through the outer most layers of periderm, due to transpiration or evaporative loss and respiration. Once the vines of a potato plant senesce or are chemically or mechanically vine killed, senescence of the underground stems and stolons also occurs. Tuber moisture content is then no longer contingent on water provided through the plants root system. After vine kill the tubers may gain or lose moisture depending on the availability of water in the soil, or water tension, and also as a factor of soil air humidity. If there is too much free moisture in the soil, tubers may become more susceptible to disease or may become highly turgid or "crisp" which may cause the ends to shatter if damaged during harvest, a disorder known as shatter bruise. Dry soil prior to harvest can result in flaccid, dehydrated tubers at the time of harvest. These tubers may be especially sensitive to pressure or may respire more as a result of moisture stress. Additionally, these tubers may be more susceptible to blackspot bruise damage during harvest (Thornton and Timm, 1990).Tuber skin maturation and suberization of the periderm that takes place after vine kill can reduce the susceptibility of the periderm to lose or gain moisture. Rapid loss of moisture from the tubers can take place at harvest and during the first weeks of bulk storage. Moisture loss at harvest appears to be greatest in potatoes that are not fully matured or have poorly set skin (Thornton and Bohl 1998). Moisture loss during harvest results from the removal of the tubers from the soil as they are maneuvered through the harvester and loaded onto trucks for transport to storage. Harvesting in low relative humidity during the warmer part of the day, followed by transport in open air vehicles can increase dehydration of the tubers. The difference in temperature and humidity between the tuber and the environment during harvest and storage is the vapor pressure deficit (Olsen and Odberg, 2003). The greater the vapor pressure deficit, the more moisture can be lost due to transpiration from the tuber during harvest and storage. Transpiration may account for 90% of tuber weight loss and is mostly due to diffusion of water vapor through the skin to the surrounding air. Within the pile of stored potatoes, tubers near the bottom will dehydrate the most due to proximity to the inflow of cool ventilation air. The estimated weight loss due to transpiration is 5 to 10 % of total tuber weight during 8 to 9 months of storage. Mature potatoes respire at a rate of 5 ml O_2/kg/h (Rastovski et al, 1981). This corresponds to approximately 1.5% weight loss during 8-10 months of storage. Shrinkage loss is greater during the early part of the storage season due to factors such as higher tuber respiration rates, higher storage temperatures, and higher transpiration. During the preliminary period of storage, tubers wound heal by developing a suberized layer, which retards water evaporation during the subsequent storage duration.

Tuber moisture loss begins to increase again as tuber dormancy (quiescence), a naturally occurring duration of reduced respiration, ends and tubers in storage begin to ”wake up”. Sprout formation, which often begins at the end of the period of physiological rest will cause additional moisture loss. As a result, effective sprout control is necessary to minimize potato dehydration and therefore pressure flattening, during long durations of storage. The pressure flattened areas are made up mostly of crushed periderm (Lulai et al. 1996) and can become a source of moisture loss after removal from storage because they are more susceptible to evaporation from damaged cells (Lulai et al. 1996).

Large reductions in the height of piled potatoes or storing potatoes for only a few months may not be practical alternatives to current methods. Therefore reducing moisture loss from tubers was considered to be the most economical and practical approach for preventing or reducing pressure flattening. Recommendations had been developed to minimize moisture loss and damage at harvest that may contribute to pressure flattening (Thornton and Bohl, 1998) These recommendations are based on minimizing physical damage to tubers at harvest and providing optimum temperatures and humidity for the crop during bin loading to minimize stress and moisture loss (Thornton and Bohl 1998, Smittle et al. 1974). Moisture loss during the storage season can be reduced by maintaining above 95% relative humidity in the air supplied for tuber ventilation and also by maintaining tuber quiescence through sprout inhibiting treatments (Caldiz et al. 2001 and Pavlista, 2005). However, even storage operations that utilize these recommendations may have severe economic losses due to pressure flattening. Experimentation was conducted in 2009- 2010 to determine if there were cultivar specific differences in pressure flattening development in response to initial moisture loss, and to determine the potential of moisture loss at harvest and during the early storage to increase pressure flattening development. After identifying dry soil prior to harvest as a potential source of tuber moisture loss and therefore a potential source of increased pressure flattening during storage, research was also conducted in 2010-2011 and 2011-2012 to determine if post vine dessication irrigation would reduce pressure flattening.

Pile height and storage duration

Pressure flattening occurs as the tuber surface becomes depressed or flattened due to constant contact from a portion of an adjacent tuber. The area of contact also receives the force exerted by the adjacent tuber as a result of the weight of tubers above it in the pile. This pile pressure is approximated as 655 kg/m^3 of pile above the potato (Muthukumarappan, et al. 1994). Potato growers and shippers often store russet potatoes in bulk piles up to 6 m. in height. In the San Luis Valley of Colorado, specialty potato cultivars such as fresh market red and yellow potatoes are also stored in pile heights up to 6 m. Within the higher bulk stored piles, 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 Helickson, 1983) The development of pressure flattening is often proposed to result from the interaction of three factors; pressure within the pile, duration of storage, and tuber moisture loss (Muthukumarappan, et al. 1994). Examining the factors individually allows for better understanding and developing strategies to limit pressure flattening. Large reductions in the height of piled potatoes or storing potatoes for only a few months may not be economical alternatives to current methods focused on moisture loss prevention. However, it may still be important to understand the extent to which the pile height of bulk stored potatoes and storage duration are responsible for pressure flattening development. It may be that for higher value specialty potatoes, a significant reduction in pressure flattening would be economically justifiable, even if the costs of storage and shipping were increased due to reduced pile height. Data is presented to show some initial research results on the effects of different simulated pile heights on pressure flattening development. Also, the summation of different treatments and cultivars that were stored at 3 and 6 months storage duration over the past 3 years is presented to provide insight into the development of pressure flattening in response to duration of storage.

Materials and Methods

Moisture Loss At-harvest and Post Vine-Kill Irrigation Study Methodology

For the study of at-harvest moisture loss and cultivar effects, potatoes were selected from field plots grown at the San Luis Valley Research Center, Colorado during the 2009 growing season. The potato fields received standard irrigation and pest control applications as needed. Applied nitrogen fertilization wused a 32-0-0 liquid fertilizer at 123 kg per hectare, including 67 kg applied before planting. Potatoes were planted during the week of 12th May 2009 and vine killed using sulfuric acid during the first week of September 2009. Tubers were mechanically harvested during the week of 21st September 2009. Eighteen samples of ten tubers (170 g to 340 g) from each of the cultivars; Canela Russet, Rio Grande Russet, Russet Norkotah, and Centennial Russet were placed in 4 kg. plastic mesh bags and weighed. One half of the samples was placed in a 37°C drying oven for 24 hours, and then reweighed to determine weight loss (moisture loss). The remaining samples were held in ambient air (18°C, 40% RH) for 24 hours and then reweighed. After treatment all samples were stored at 3°C and 95% RH prior to placement into the ventilated container system to induce pressure flattening. The mesh bags set aside at harvest were then placed into three sets of ventilated containers. Three sample bags from each cultivar and treatment were placed in each set of ventilated containers. One set of containers would be disassembled and the sample tubers evaluated after 3 months, another set after 5 months, and a third set after 6 months storage duration. The ventilated container apparatus, as described earlier, was designed to test tuber susceptibility to pressure flattening when exposed to ventilation, time, and pile pressures similar to those found in commercial potato storages. The six filled containers were placed tightly together with a continuous air exchange tube beneath them.

After the desired storage duration, sample bags were removed from the containers, weighed to determine weight (moisture) loss during storage and then assessed for pressure flattening. Pressure flattening was evaluated for each tuber within each sample bag. Tubers were visually inspected and each flattened area was circled, numbered in ascending order using permanent markers, and its diameter measured. The field plots to study the effects of post vine kill irrigation was established at the San Luis Valley Research Center, Colorado during the 2010 and 2011 growing seasons. The potato fields received standard irrigation and pest control applications as needed. Potatoes were planted during the first week of May in 2010 and the second week of May in 2011. In 2010, the plots were established as two, 30 m. by 12 row sections, each separated by a 10 m. non-planted border. On both sides of the plots, parallel to the sections and border areas were sets of standard sprinkler lines which provided irrigation at a rate of roughly 1.2 cm. per hour. The four cultivars, Canela Russet, Colorado Rose, Russet Norkotah Selection 8, and Rio Grande Russet, were planted in two row strips, approximately 15 m. long and randomized to be planted three times within each section. After planting, two sets of digital tensiometers, connected to a data logger and 3 sets of plastic 10 cm. capacity rain gauges were placed in the ground for each section The plots were vine killed using sulfuric acid during the first week of September 2010. After vine kill sprinkler lines were detached along the length of the plot so that only one section (and part of the 10 m. buffer) would receive the weekly ½ inch irrigation effects. The experimental setup was similar for the 2011 field experiment, except that three sections were established and sprinkler heads were modified to ensure one section received 1.2 cm. irrigation each week and the next section received 0.6 cm. weekly. For both years tarpaulins were used to cover the control section when precipitation was anticipated with mixed results due to frequent displacement by high winds. Immediately prior to harvest rain gauges and moisture sensors were removed. Tubers were mechanically harvested during the first week of October 2010 and the second week of October in 2011. Broken and rotten tubers were not collected and yield was not measured. The tubers from the same cultivar and treatment section were mixed together. Thirty samples of five tubers (170 g to 340 g) from each of the cultivars and treatments were placed in 2 kg. plastic mesh bags, labeled and weighed. These mesh bags were then placed into three sets of ventilated containers. Ten sample bags from each cultivar and treatment were placed in each set of ventilated containers. One set of containers would be disassembled and the sample tubers evaluated after 3 months, another set after 6 months, and a third set after 9 months storage duration. The set of samples stored for 9 months was discarded due to excessive sprouting. The samples had not been treated with sprout inhibitors because the containers were being kept in a storage normally used to store seed potatoes. After the predetermined storage duration, the sample bags were removed from the containers, weighed to determine weight (moisture) loss during storage and then assessed for pressure flattening. Pressure flattening was evaluated for each tuber within each sample bag. Tubers were visually inspected and each flattened area was circled, numbered in ascending order using permanent markers, and its diameter measured.

In order to better evaluate the data from the tensiometers, during the winter months tensiometers were placed in a 15 l. plastic pot filled with field soil from the plots. The pot, which included holes at the bottom to allow for drainage of water that exceeded the soils field capacity, was then saturated with water, weighed and the tensiometer measurements recorded. Every few days the pot was weighed again and tensiometer meetings recorded until the soil was very dry. This was done so that the relationship between the percent of soil water capacity of the field soil at the station and the tensiometer readings could be established and therefore results from the tensiometers in the field experiments could be converted accurately into percent of soil water holding capacity.

Pile Height and Storage Duration Methodology

An initial evaluation of the effects of simulated pile heights is being conducted in 2012-2013. Two hundred (113-283g.) tubers were collected at harvest for 15 separate cultivars from tubers being unloaded at the commercial storage. These tubers were then kept in a climate controlled corridor at 15 degrees C and approximately 95% relative humidity until all samples had been collected. Twenty tubers from each cultivar were evaluated for peak load required for 3mm surface deformation at harvest. The remaining one hundred eight tubers of each cultivar were divided into thirty labeled plastic mesh bags, each containing six tubers. 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. Six ventilated containers were used, to allow for three different pile heights (3.1 meters, 3.7 meters, and 4.6 meters) at 2 different storage durations (3 month and 6 month). The ventilated container system was modified by reducing the amount of water in the plastic tank above the container that is used to provide additional weight. The differences in the fill level of the tanks would allow for pressures on the samples to change, creating the different simulated pile heights. The comparisons between at-harvest peak load and the resulting pressure flattening per tuber are presented with the data about the accuracy of texture analysis as a predictive tool (Section 2 Results). To examine the general effect of storage duration on pressure flattening development, data was averaged for the different treatments and cultivars that were stored at 3 and 6 months storage duration over the past 3 years.

Statistical Analysis

For the moisture loss and cultivar study tubers were randomly selected from among freshly harvested tubers that had been loaded into storage. Tuber samples in the crib were arranged in randomized fashion within the described sample zone. Data analysis was performed using two factor analysis of variance at $\alpha=0.05$ using SAS (Version 9.2). Data for individual tubers was analyzed within each sample bag. Pressure flattened area and bruise number per tuber were analyzed using LS means procedure to account for samples affected by rot and therefore containing some tubers that were not usable. Error bars in figures and means separation in tables using letter based groupings are based on a calculated Fishers LSD at $\alpha=0.05$ using the standard error and an approximated T-value of 2.

The field trials to study the effect of post vine kill irrigation were a split plot design in which cultivars were randomly planted within blocks in each treatment section but the treatment areas were separate sections arranged based on distance along the length of the irrigation system. As a result, there was no randomization of the treatments. Tubers that were tested or subjected to pressure flattening were randomly selected from among 227-340g. 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 a single factor 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, with the bag average being used as a replicate. Decayed, diseased, or broken tubers were discarded and the average for each bag did not include these tubers. Error bars in figures and means separation in tables using letter based groupings are based on a calculated Fishers LSD at $\alpha=0.05$ using the standard error and an approximated T-value of 2. In the study on the effect of pile height, tubers that were tested or subjected to pressure flattening were randomly selected from among 113-283g. tubers that were being loaded into bulk storage. The tuber samples placed in the ventilated container design were arranged in randomized fashion within the described sample zone. Data for individual tubers was averaged within each sample bag, with the bag average being used as a replicate. The averaged pressure flattened area per tuber for all bags, regardless of cultivar, that were stored at each simulated pile height were used as a replicates to compare different pile heights. Data analysis for pressure flattening comparisons among treatments was performed using a single factor analysis of variance at $\alpha=0.05$ using the data analysis toolpak in Microsoft Excel 2007. The error bars in the figure are based on a calculated Fishers LSD at $\alpha=0.05$ using the standard error and an approximated T-value of 2.

Results

Effects of At-harvest Moisture Loss and Cultivar on Pressure Flattening Development

More moisture loss was observed in the oven dry samples than the air dry samples, regardless of cultivar (Figure 50), and there were significant differences among the cultivars. For example, Centennial Russet had greater weight loss (4.99%) than the other cultivars and Russet Norkotah (3.82%) had less than Centennial but more than Canela Russet (2.93%) or Rio Grande Russet (3.24%) for the oven treated tubers. After 25 weeks of storage, weight loss from oven dry Centennial Russet (6.16%) tubers was significantly greater than the air dry Centennial Russet tubers (4.38%) (Figure 51). The other cultivars did not have significant differences in weight loss during storage attributable to the at harvest treatments. Russet Norkotah tubers lost the least amount of weight during 25 weeks of storage among the four cultivars.

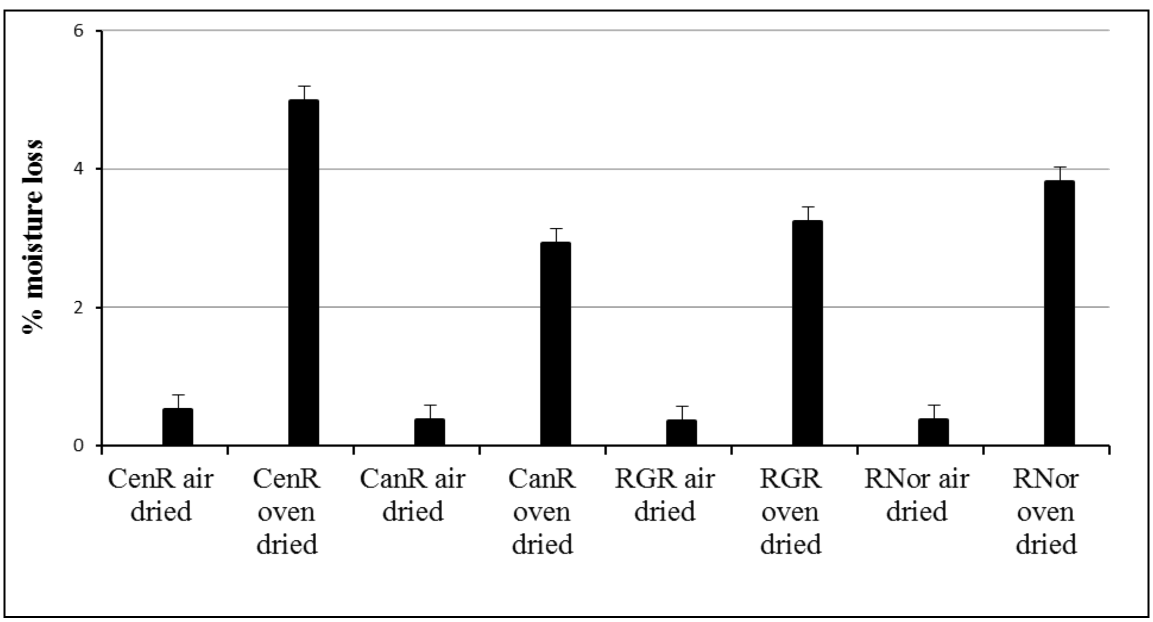

Figure 50. Weight loss following moisture loss treatments. Oven dry tubers were placed in a drying oven at37°C for 24 h. Air dry tubers were held at approximately 18 C for 24 h. Error bars represent the calculated least significant difference (LSD) for the least square means given α=0.05. Error bars that overlap indicate no significant difference between those treatments. Cultivars names are abbreviated as follows: CanR is Canela Russet, CenR is Centennial Russet, RGR is Rio Grande Russet and RNor is Russet Norkotah.

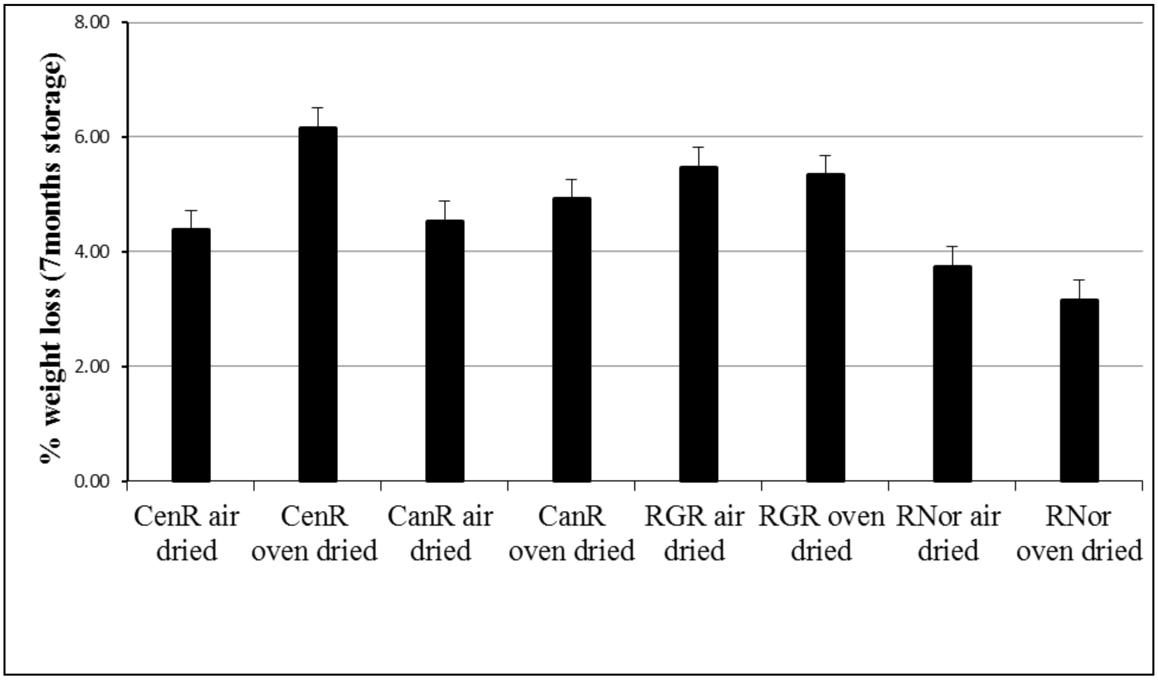

Figure 51. Weight loss by cultivar and treatment during storage at 4 C and 95% RH following the moisture loss treatments described in Figure 1. Error bars represent the calculated LSD for the least square means given α=0.05. Error bars that overlap vertically indicate no significant difference between treatments. Cultivars names are abbreviated as in Figure 44.

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More pressure bruise areas per tuber were observed in the oven dry treatments compared to the air dry treatments between 21 and 25 weeks of storage (Figure 52). Similarly, tubers in the oven dry treatments had significantly more flattened area per tuber than tubers from the air dry treatments after 21 and 25 weeks of storage (Figure 53). The total area of pressure flattening in oven dry tubers intersected the line indicating 18cm^2 (the area of flattening allowable by the USDA grade standards) approximately 2 weeks earlier than the air dry treated tubers.

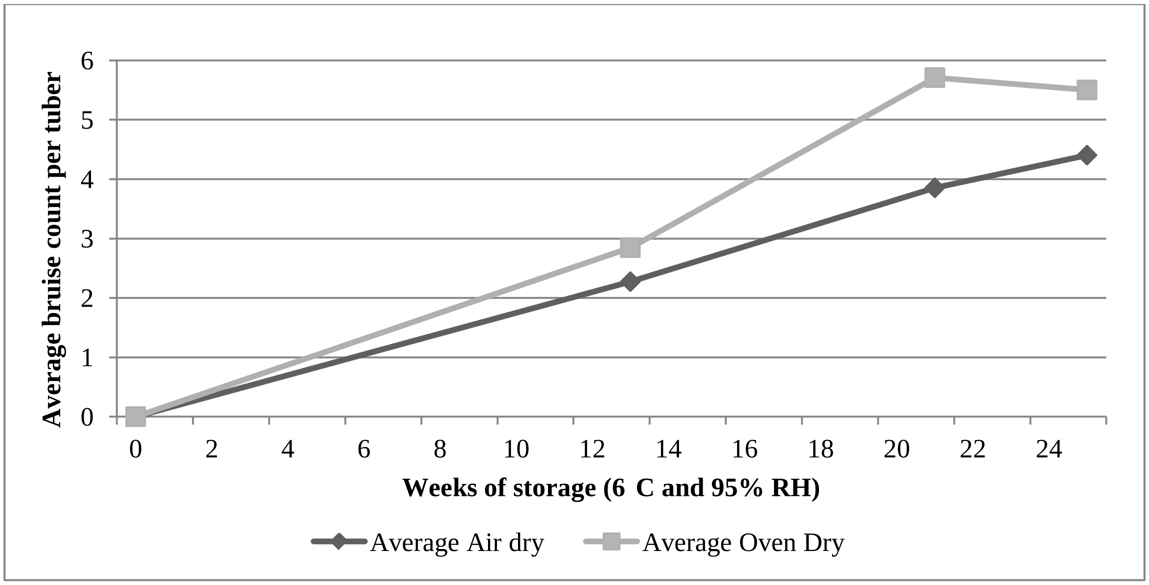

Figure 52. Mean number of bruises per tuber by treatments described in Figure 2 after storage at 4 C and 95% RH. Values are least square means averaged for all cultivars. Error bars represent the calculated LSD given α=0.05.

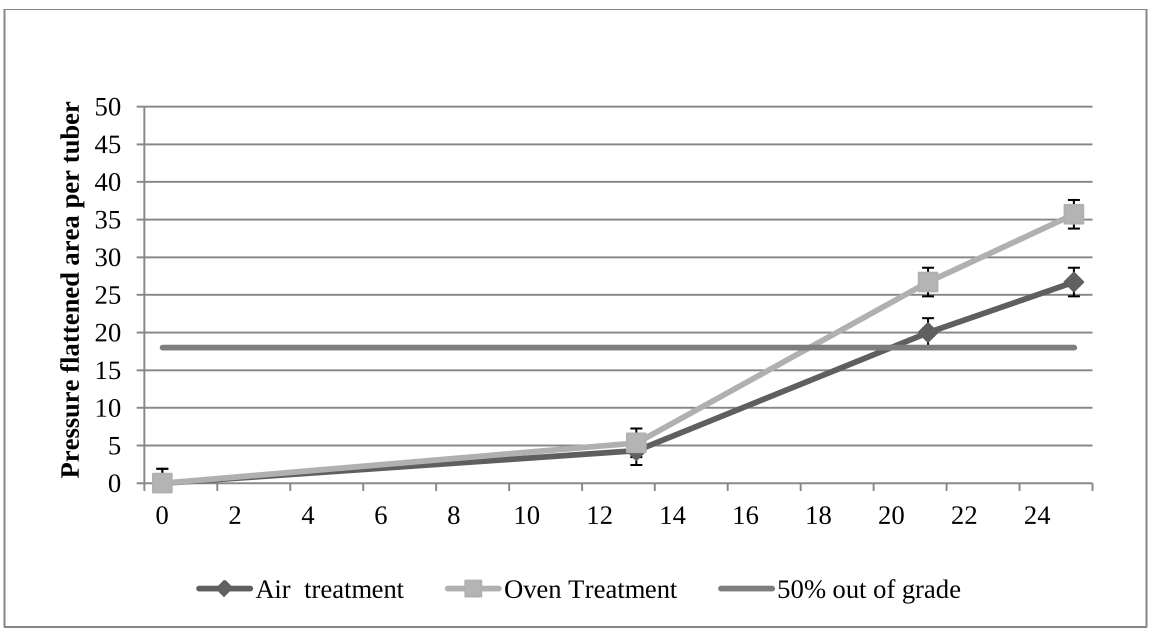

Figure 53. Mean flattened area per tuber (cm^2) by treatments as described in Figure 2 after storage at 4 C and 95% RH. The dotted line indicates a flattened area of 18 cm^2, at which a 227-340 g tuber is considered out-of-grade according to the USDA potato quality and grade standards. Error bars represent the calculated LSD for the least square means given α=0.05.

It is interesting to compare the increase in pressure bruised area within a cultivar by treatment with the amount that results in tubers that are pressure flattened in excess of 18 cm^2 and therefore below the quality needed as a US No. 2 potato. For Canela Russet there was no significant difference in the area of pressure flattening per tuber at the three storage durations tested (Figure 54 A). The difference of in the time to reach 18 cm^2 of flattened area in the air dry tubers and oven dry Canela Russet tubers was only about one week. Centennial Russet had no differences attributable to moisture loss treatments in the amount of pressure flattening per tuber at any of the three storage durations tested (Figure 54 B). This is despite significant differences in both at-harvest moisture loss treatments (Figure 50) and weight loss during storage (Figure 51).

The number of pressure flattened areas of Rio Grande Russet tubers is not significantly different between moisture loss treatments at the three storage times (Figure 54 C). Although the pressure flattened areas per tuber are lower for the air dry treatment, the differences are not significant. However, the air dry tubers reached 18cm^2 of flattened area approximately 3 weeks later than the oven dry tubers. Pressure flattened areas of Russet Norkotah did not differ for air dry vs. oven dry at 13 weeks of storage, but the differences at 21 and 25 weeks of storage were significant (Figure 54 D). Air dry tubers had 18cm^2 of flattened area six weeks later than the oven dry tubers.

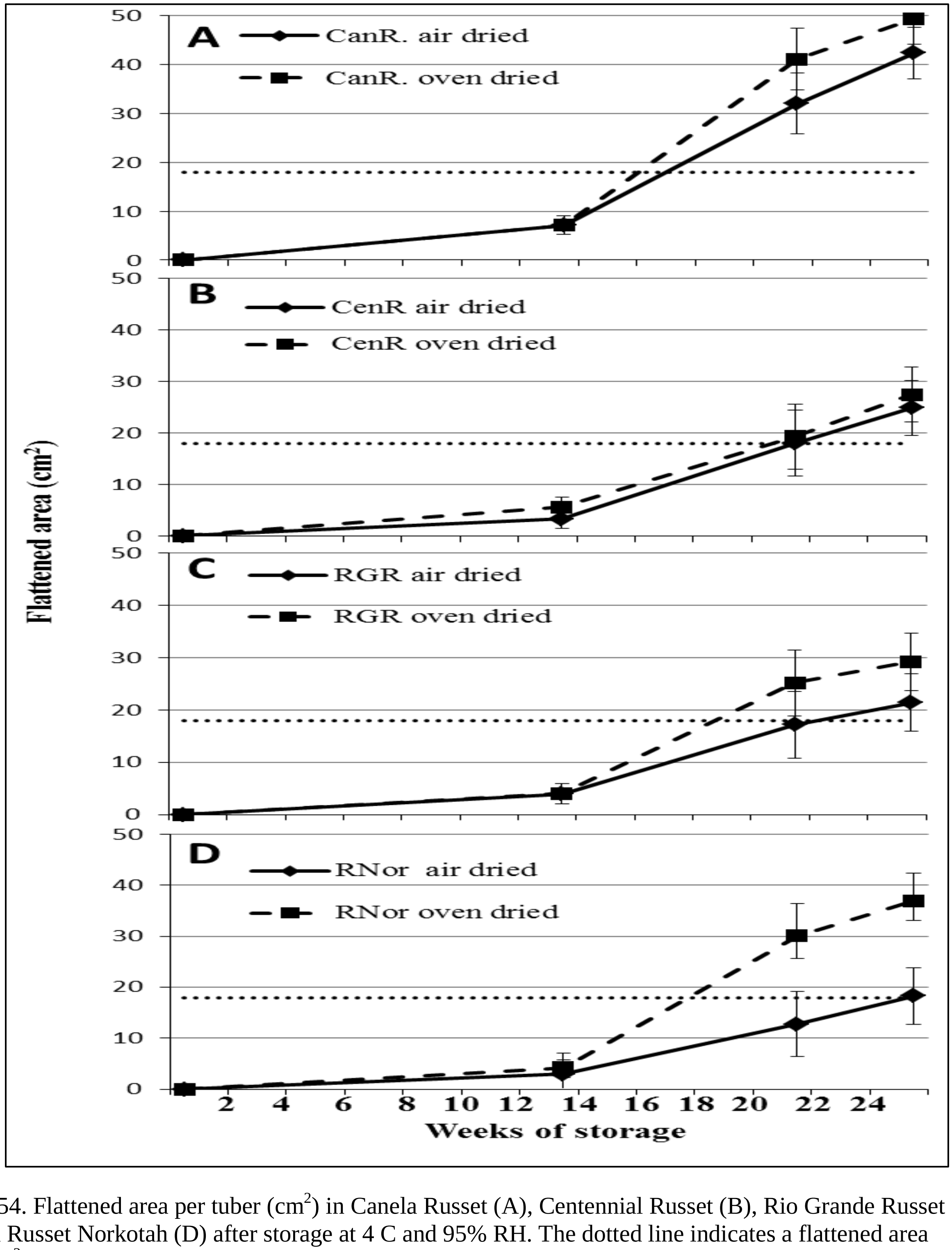

Figure 54. Flattened area per tuber (cm^2) in Canela Russet (A), Centennial Russet (B), Rio Grande Russet (C) and Russet Norkotah (D) after storage at 4 C and 95% RH. The dotted line indicates a flattened area of 18 cm^2 as noted in Figure 5. Values are least square means. Error bars represent the calculated LSD for the least square means given α=0.05. Cultivars names are abbreviated as in Figure 44.

The number of pressure bruised areas per tuber was significantly greater for both air and oven dry treatments of Canela Russet compared to air dry Centennial Russet and air dry Russet Norkotah after 13 weeks of storage (Table 9). At 21 and 25 weeks of storage, air dry Russet Norkotah had fewer bruised areas compared to oven dry Russet Norkotah. After 21 weeks of storage, in cultivars Russet Norkotah, Rio Grande Russet and Canela Russet air dried tubers had significantly fewer bruised areas tubers of the same cultivar from oven dry treatments. However, at 25 weeks only Russet Norkotah still showed this difference.

Table 9. Number of bruised areas per tuber after storage at 4°C and 95% RH. Values presented are least square means. Values within a column denoted by the same letter are not significantly different at α=0.05. Cultivars names are abbreviated as in Figure 41.

			Number of Flattened Areas/Tuber	
Cultivar and Treatment	Initial loss in %	13 weeks storage	21 weeks storage	25 weeks storage
CanR air dry	0.4	3.3 B	5.2 BC	5.8 CD
CanR oven dry	2.9	3.4 B	6.8 D	7.1 D
CenR air dry	0.5	2.1 A	4.0 B	4.6 ABC
CenR oven dry	5.0	2.8 AB	4.6 BC	5.3 BC
RGR air dry	0.4	2.1 AB	3.5 AB	3.9 AB
RGR oven dry	3.2	2.8 AB	5.8 CD	4.6 ABC
RNor air dry	0.4	1.6 A	2.7 A	3.3 A
RNor oven dry	3.8	2.4 AB	5.6 CD	5.0 BC

The pressure flattened area per tuber was significantly greater for Canela Russet in both treatments compared to air dried Centennial Russet and air dried Russet Norkotah after 13 weeks of storage (Table 10). After 21 and 25 weeks of storage, the pressure flattened area per tuber was also significantly higher for Canela Russet for both treatments compared to both treatments of Centennial Russet, Rio Grande Russet, and air dried Russet Norkotah.

Table 10. Flattened area per tuber (cm^2) after storage at 4°C and 95% RH. Values presented are least square means. Values within a column denoted by the same letter are not significantly different at α=0.05. Cultivars names are abbreviated as in Figure 41.

		Pressure flattened area/ tuber		
Cultivar and Treatment	Initial loss in %	13 weeks storage	21 weeks storage	25 weeks storage
CanR air dry	0.4	7.0 B	32.0 CD	42.0 CD
CanR oven dry	2.9	7.0 B	41.0 D	49.0 D
CenR air dry	0.5	3.0 A	18.0 AB	25.0 AB
CenR oven dry	5	6.0 AB	19.0 AB	27.0 B
RGR air dry	0.4	4.0 AB	17.0 AB	21.0 AB
RGR oven dry	3.2	4.0 AB	25.0 BC	29.0 B
RNor air dry	0.4	3.0 A	13.0 A	18.0 A
RNor oven dry	3.8	4.0 AB	30.0 C	37.0 C

Soil moisture sensor readings were averaged and converted to percent of soil water capacity to determine the effect on soil moisture of the control (no additional irrigation) versus the 1.2 cm. per week irrigation treatment (Figure 55). The results indicate that while the soil moisture declined for both the control and treatment following vine kill, the percent soil water capacity stayed above 75% for treated areas, while declining below 65% for the control areas.

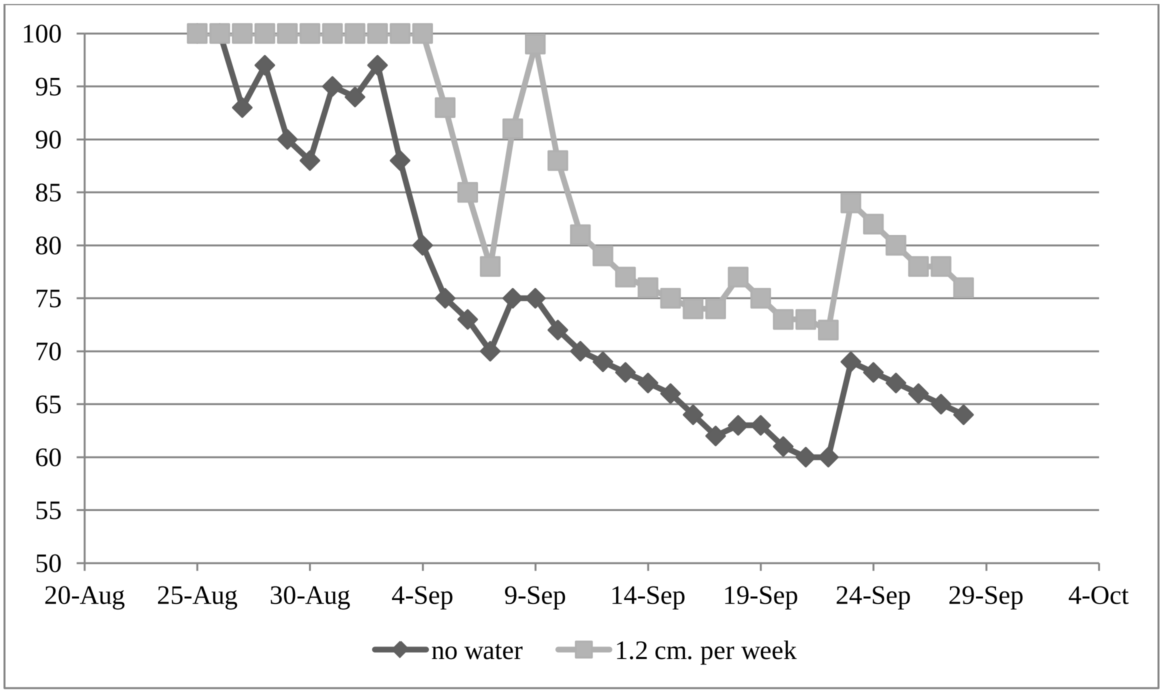

Figure 55. Soil moisture content as percent of field capacity by post vine kill irrigation treatment from vine kill until harvest(Fall 2010).

The pressure flattening per tuber data (Table 11 and Figure 56 and Figure 57) indicates a trend toward increased pressure flattening for Russet Norkotah treated with the additional irrigation and stored for three months(28.1 cm^2 vs. 17.7 cm^2 for the control). At the six month storage duration, Colorado Rose produced a statistically significant increase in pressure flattening when additional irrigation was applied (49.5 cm^2 vs. 37.0 cm^2 for the control).

Table 11. Pressure flattened area per tuber (cm^2) for each cultivar by post vine kill irrigation treatment after 3 and 6 months storage duration (2010-2011).

Cultivar	Treatment	3 month storage	6 month storage
Colorado Rose	1.2 cm. per week	36.2 NS	49.5 B
	Control	42.2 NS	37.0 A
Canela Russet	1.2 cm. per week	27.3 NS	43.0 NS
	Control	26.5 NS	35.3 NS
Rio Grande	1.2 cm. per week	28.0 NS	44.6 NS
	Control	32.9 NS	35.8 NS
Russet Norkotah	1.2 cm. per week	28.1 NS	39.4 NS
	Control	17.7 NS	38.3 NS

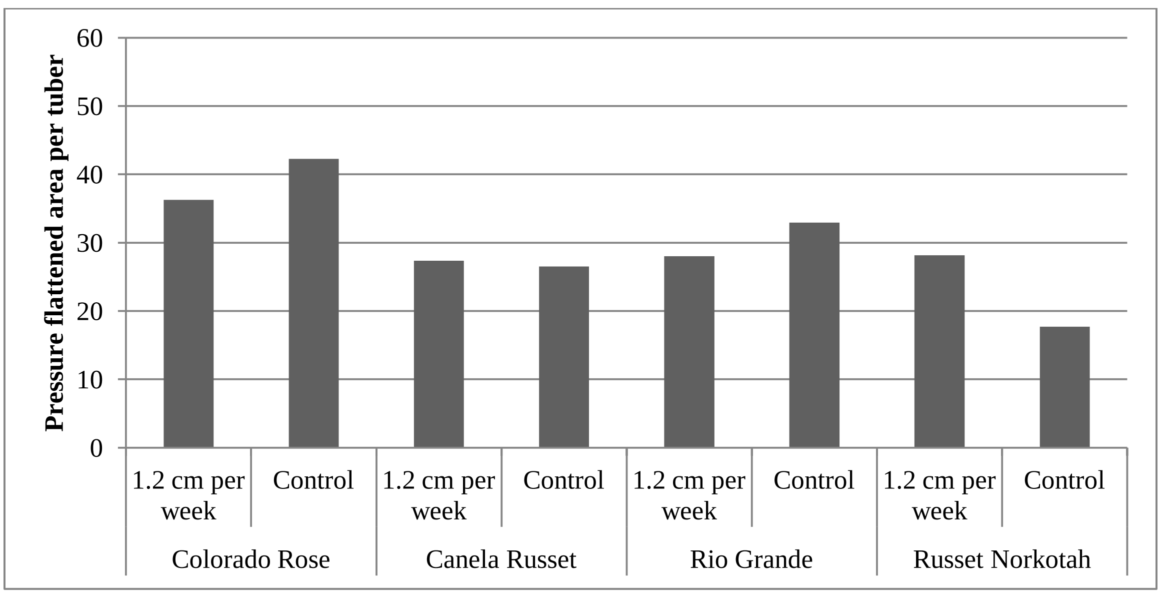

Figure 56. Pressure flattened area per tuber (cm^2) for each cultivar based on post vine kill irrigation treatment after 3 month storage duration (2010-2011 data).

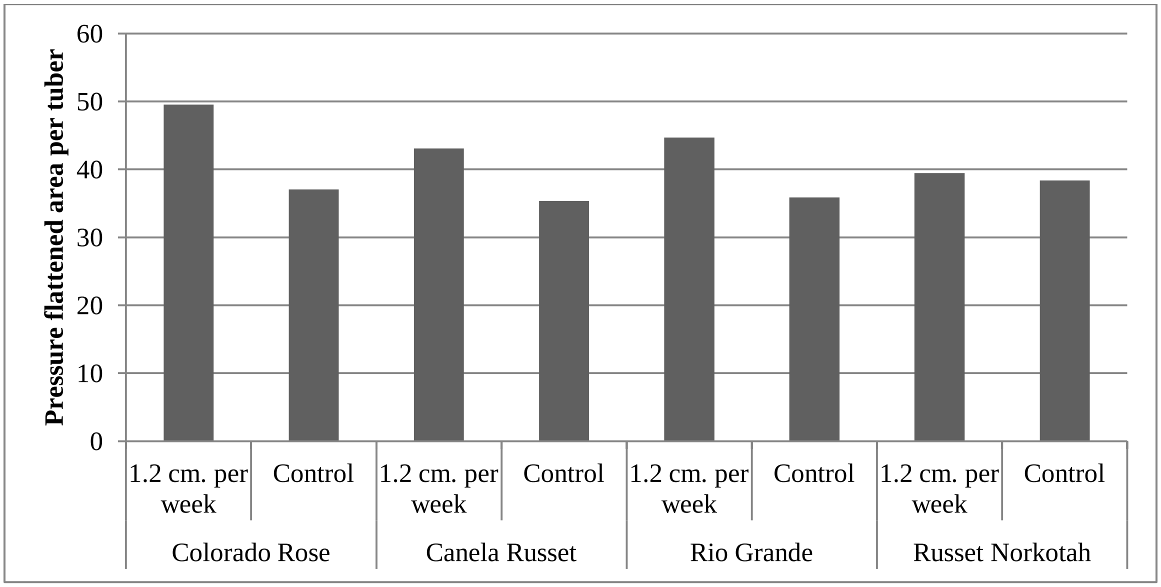

Figure 57. Pressure flattened area per tuber (cm^2) for each cultivar based on post vine kill irrigation treatment after 6 month storage duration (2010-2011 data).

Data from the soil moisture sensors for the 2011-2012 study of post-vine kill irrigation effects on pressure flattening development are represented in Figure 58. The results indicate little or no difference in the percent of filled soil moisture capacity between the 1.2 cm. per week and 0.6 cm. per week irrigation treatments. For most of the period after vine kill, the percent of soil moisture capacity for the two treatments was between 67% and 72%. For the non-irrigated control, the soil moisture capacity steadily decreased and fell below 65% during the last week before harvest.

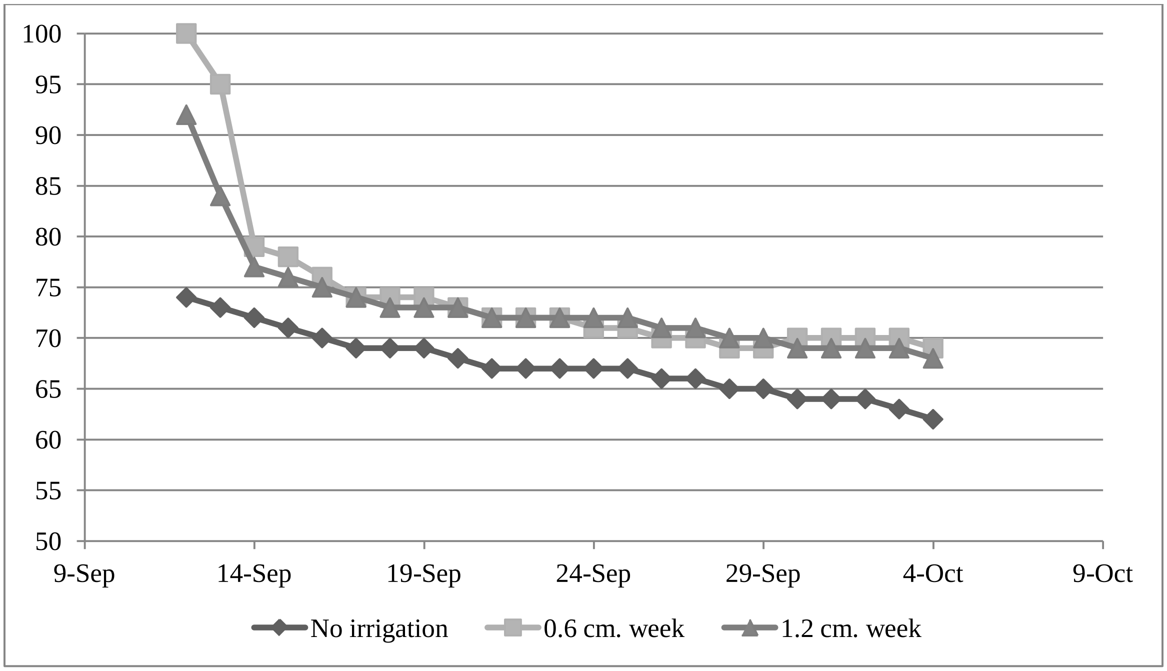

Figure 58. Soil moisture content as percent of field capacity by post vine kill irrigation treatment from vine kill until harvest(Fall 2011).

Pressure flattening results from the 2011-2012 experiment indicate significant increases in pressure flattened area per tuber for some of the cultivars in response to the irrigation treatments (Table 12 and Figure 59 and Figure 60). In the three months storage duration data there is a trend toward increased pressure flattened area for the Canela Russet that were given 0.6 cm. irrigation per week and for Rio Grande provided 1.2 cm. irrigation per week. After 6 months storage duration there was a statistically significant increase in pressure flattened area for the Canela Russet without additional water (33 cm^2) compared to the 1.2 cm. per week irrigation treatment (26 cm^2).

Table 12. Pressure flattened area per tuber (cm^2) for each cultivar by post vine kill irrigation treatment after 3 and 6 months storage duration (2011-2012).

Cultivar	Treatment	3 month storage	6 month storage
Canela Russet	Control	9.9 NS	33.3 B
	0.6 cm. per week	19.1 NS	29.9 AB
	1.2 cm. per week	11.9 NS	26.0 A
Colorado Rose	Control	10.3 NS	28.2 NS
	0.6 cm. per week	11.4 NS	34.9 NS
	1.2 cm. per week	13.0 NS	26.6 NS
Russet Norkotah	Control	11.0 NS	20.9 NS
	0.6 cm. per week	11.1 NS	22.1 NS
	1.2 cm. per week	9.0 NS	18.8 NS
Rio Grande	Control	13.7 NS	28.8 NS
	0.6 cm. per week	11.4 NS	31.8 NS
	1.2 cm. per week	19.2 NS	36.3 NS

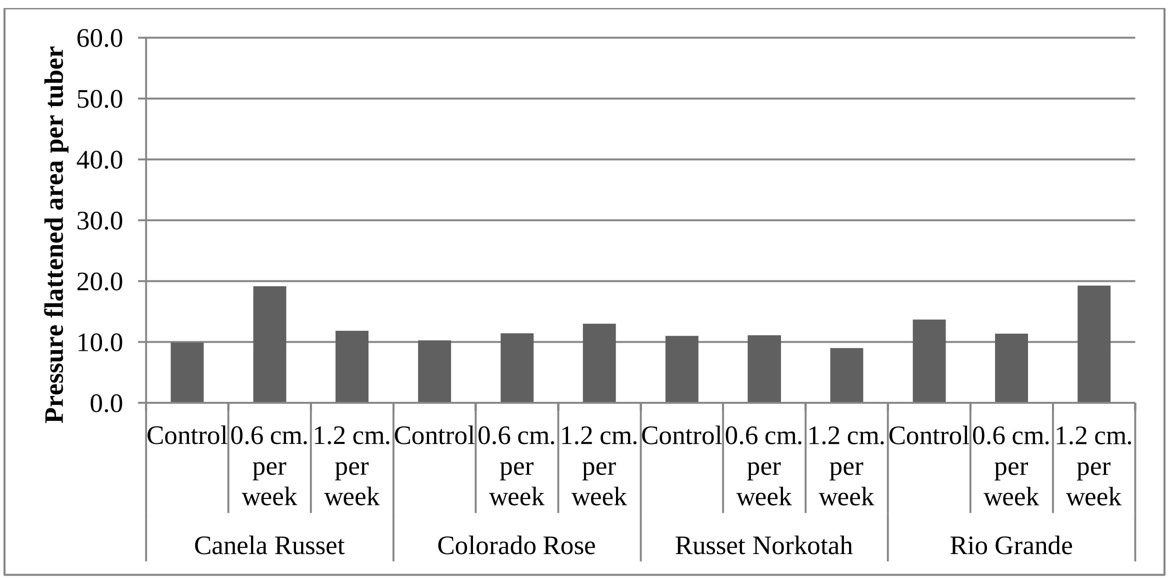

Figure 59. Pressure flattened area per tuber (cm^2) at 3 months storage duration for each cultivar based on post vine kill irrigation treatment (2011-2012 data).

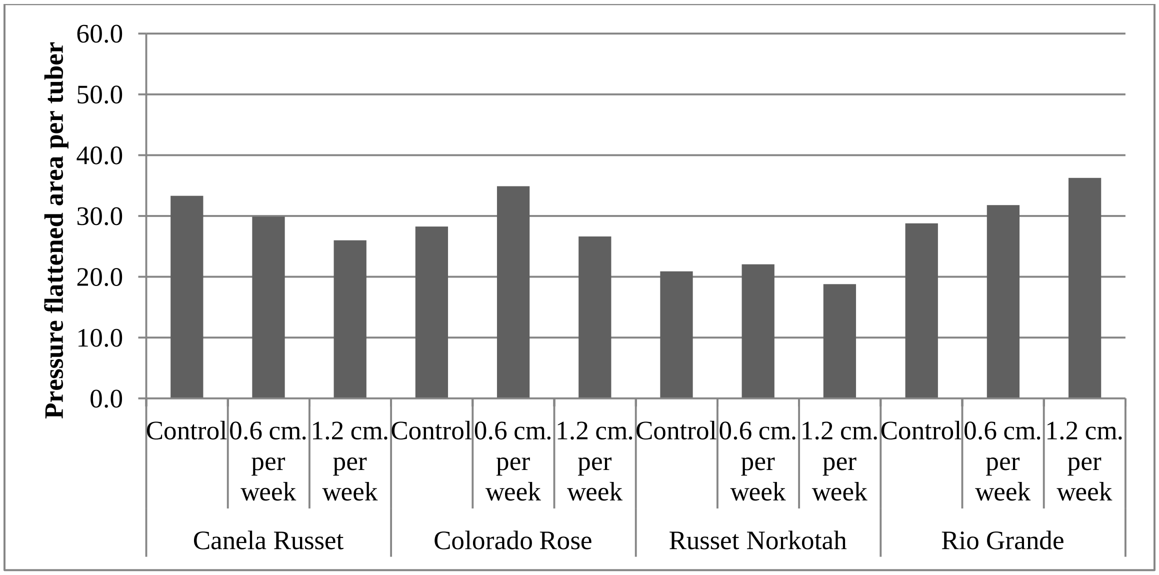

Figure 60. Pressure flattened area per tuber (cm^2) at 6 months storage duration for each cultivar based on post vine kill irrigation treatment (2011-2012 data).

Effect of Pile Height and Storage Duration:

The results of preliminary experimentation to study the effect of different simulated pile heights on pressure flattening development show statistically significant increases as pile height is increased (Figure 61). There was a modest, although statistically significant, increase in flattened area per tuber as simulated pile height was increased from 3.1 m. to 3.7 m. (7.64 cm^2 vs. 9.11 cm^2). The pressure flattened area from the 4.6 m. pile height (13.25 cm^2) was dramatically higher in comparison to the flattened area per tuber for the 3.1 m. and 3.7 m. (9.11 cm^2 and 7.64 cm^2 respectively).

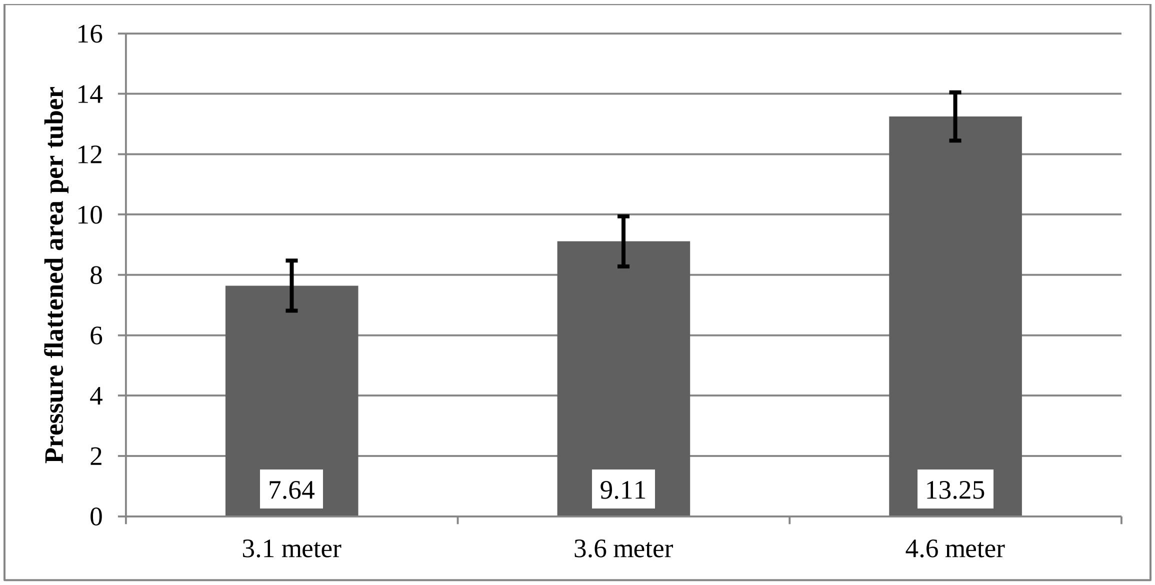

Figure 61. Comparison of pressure flattened area per tuber (cm^2) based on pile height after 3 months storage duration (averaged across all samples and cultivars).

There appeared to be a linear increase in the overall mean number of bruised areas per tuber until 21 weeks of storage (Figure 62). Between the 21 and 25 weeks of storage there was no increase in the mean number of pressure bruises per tuber. This suggests that the contact points between adjacent tubers that will result in pressure flattening are established. There are on average four to six such areas of contact for each tuber within a tuber pile (Figure 62). The flattened area per tuber continued increase linearly after 21 weeks of storage (Figure 63). This suggests that the an increase in pressure flattening for potatoes stored more than 21 weeks is due to an increase in the diameter of individual areas rather than an increase in the numbers of areas.

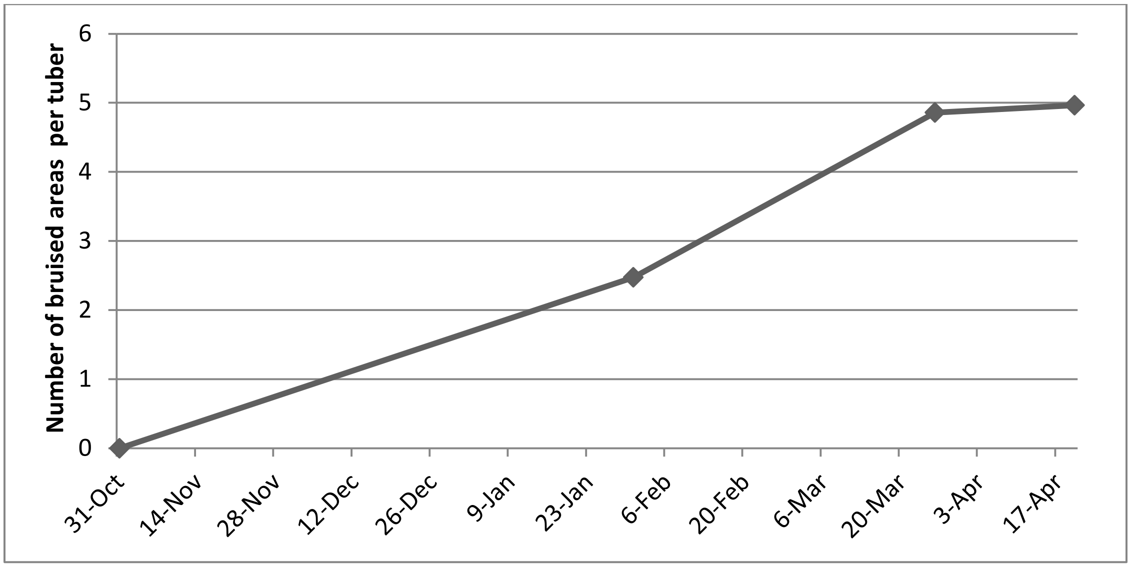

Figure 62. Averaged bruises per tuber for all samples regardless of cultivar and treatment observed after 3, 5, and 6 months of storage at 4 degrees C and 95% relative humidity. Values are averages of the least square means for all treatments and cultivars.

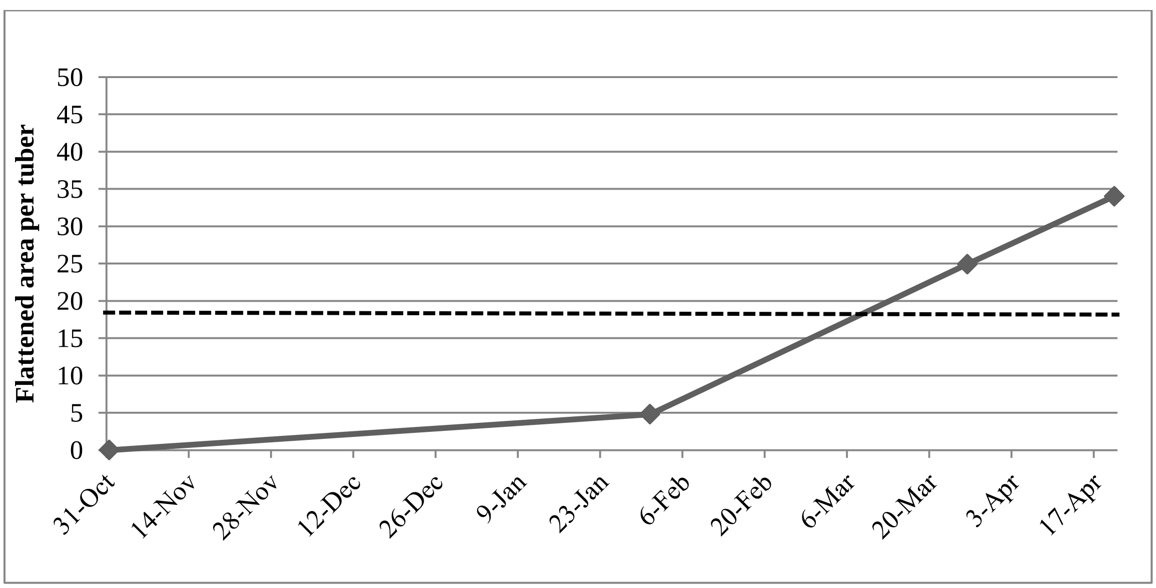

Figure 63. Averaged flattened area per tuber (cm^2) for all samples regardless of cultivar and treatment observed after 3, 5, and 6 months of storage at 4 degrees C and 95% relative humidity from the 2009-2010 cultivar by moisture loss study .Values are averages of the least square means.

Results averaged from the experiments in 2010-2011 and 2011-2012 show year to year differences bust still show an overall linear increase in the pressure flattened area per tuber (Figure 64).

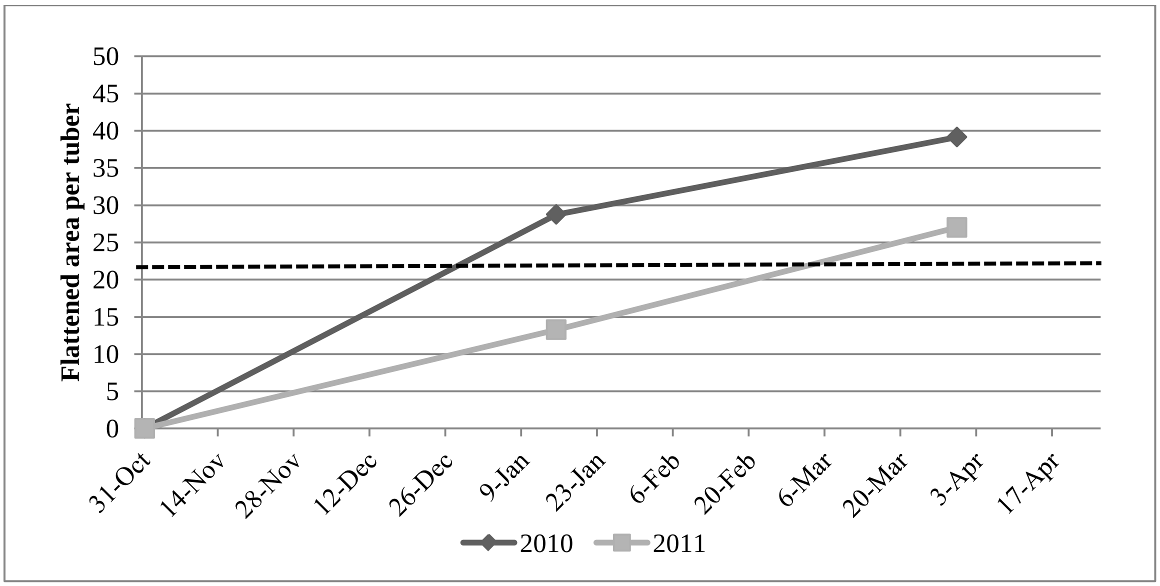

Figure 64. Averaged flattened area per tuber (cm^2) for all samples regardless of cultivar and treatment observed after 3 and 5 months storage duration for the 2010-2011 and 2011-2012 storage seasons.

DISCUSSION AND CONCLUSIONS

Development of a Research Methodology to Induce and Measure Pressure Flattening.

The ventilated container with water tank system successfully induced pressure flattening over the course of several months of storage. The development of pressure flattening proceeded at a rate similar to that have been observed in commercial storages in the San Luis Valley of Colorado. Early symptoms of pressure flattening are observed in December and January (13 weeks storage duration) and the bruise severity increases as time in storage increases, often exceeding grade tolerances in the months of March and April (21-25 weeks storage duration). The simulated pile pressure of approximately 2.4 m. of potatoes above the samples was found to be sufficient to produce pressure flattening in the sample zone.

The pressure flattening results from sample bag to sample bag varied considerably, which indicates a need for at least several replications of samples within the treatment area of the container. If there is a large enough volume of samples to be tested in each container, it is especially important that the samples be loaded randomly from among the treatments and cultivars so that there are some samples from each cultivar and treatment nearer to the bottom, the top, and the center of the treatment area. It is also of critical importance that tuber samples be kept for as short a duration as possible between harvest and placement in the containers. Most of the research conducted using the design allows the ventilation system to run continuously, however specific intervals of ventilation could be evaluated if the power supply to the fan was controlled using a timer. To evaluate different humidity and storage temperatures, the system would need to be assembled in a climate controlled area that could be adjusted to those parameters, since the design does not include any method to regulate temperature and humidity. Overall, the system may be refined further, but the system is successful in generating pressure flattening in a nearly identical way to the occurrence of pressure flattening in storage. Development of the ventilated container design has enabled this research to be conducted in a controlled manner, without the costs and logistics involved in conducting the experiments using multiple bulk storage bins and many tens of thousands of kilograms of potatoes.

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

The initial objective of the doctoral research program was to evaluate different fertility and plant nutrient applications to increase the duration that potatoes could be stored prior to significant pressure flattening. Due to the weight of potatoes in bulk commercial storages, and the months of storage duration, there was a concern that any management changes or recommendations developed by the field and storage based experiments could result in only minimal assistance to growers and storage operators in reducing pressure flattening. When pressure flattening was evaluated in commercially operated storages important observations were made that changed the initial objectives of the research program. Even 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, (even if the test was only moderately accurate) it would help improve returns for growers and shippers. Results from the tests applied at harvest (oven moisture loss, whole tuber rehydration, blackspot bruise incidence, specific gravity, relative water content, and resistance to 3mm. 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, only a few tests (relative water content, specific gravity, peak load required for deformation) provided any correlation. The modification of testing relative water content for leaf tissue (Dhanda and Sethi, 1998) using potato tissue cores was similar to work done with pumpkin tissue cores in which the cores themselves were evaluated for failure strain and elasticity in addition to moisture content (Mayora et. al., 2007). There was low to moderate correlation for our relative water content at-harvest results compared with the 3 and 6 month pressure flattened areas. While the relative water content results from tubers did respond to weight loss, it does not appear that, at least using our methodology, relative water content testing of tuber tissue cores would be sensitive enough to correctly identify differences in tuber weight loss of 1.5% or less. Additionally, results from our evaluations of the effect of at-harvest moisture loss and post vine kill irrigation reveal that moisture loss is not solely responsible for relative pressure flattening development (Castleberry and Jayanty, 2012). Research has suggested that potatoes with lower specific gravity may be more prone to pressure flattening development (Thornton and Bohl, 1998). The specific gravity results from at-harvest testing showed moderate correlation (R^2=0.2404 and 0.2026 at 3 and 6 months storage duration respectively) with pressure flattened area per tuber. There may 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 higher percent solids. Additionally, some cultivars such as Innovator that can have relatively high specific gravities appear to pressure flatten before lower specific gravity cultivars such as Russet Norkotah. At-harvest measurement of the peak load required to deform the surface of the tubers at harvest provided moderate to strong correlations with pressure flattened area after storage. 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. The use of a penetrometer had also been previously 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 (Zhu, 2003) theorized that greater resistance to load may 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. Because of this complexity, it is difficult for a single instrumental analysis to be highly accurate (Landahl et al. 2004). However, 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.

Evaluation of Growing Season Methods to Reduce Pressure Flattening

Effect of Cultivar on Pressure Flattening Development

At-harvest moisture loss increased the susceptibility to pressure flattening for some cultivars more than others. The significant differences between cultivars in the effects of moisture loss on pressure flattening development suggests that moisture loss (as a component of weight loss) may result in an increase in pressure flattening for some cultivars. However, cultivar specific physiological and anatomical features, such as those responsible for differences in blackspot bruise susceptibility may explain pressure flattening differences that are not directly related to tuber dehydration (Thornton and Bohl, 1998; Corsini et al. 1999). Even with the assumed substantial additional moisture loss during 25 weeks of storage, oven dry Centennial Russet tubers had less pressure flattened area per tuber than oven dried Russet Norkotah or Canela Russet from either the oven or air dried treatment. Studies of other russet cultivars have shown that mechanical resistance of tuber tissue samples can be affected by turgidity but the degree of turgidity loss that leads to tissue structural failure under pressure is likely to be cultivar specific (Bajema, et al 1998). 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). When plant tissue is compressed, the main effect is on the cell walls, which comprise the basic structural elements responsible for structural integrity of the tissue. Some of the cell wall and tissue resistance to pressure may due to “reinforcement zones” in which pectic polymer concentration increases cell adhesion (Jarvis et al. 2003). The concentration of these pectic polymers may be different for different cultivars. Higher resistance to mechanical stress is also found in smaller-sized cells but these cells may be less resistant to micro-damage (Konstankiewicz and Zdunek 2001; Zdunek and Umeda. 2005). Rate of suberization may also be different among cultivars and may require experimental study to determine if it is an important factor in storability. When other factors are accounted for, the differences in pressure flattening development between cultivars are significant. The data strongly suggests that some cultivars can be stored for much longer durations than others before pressure flattening becomes severe. 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. 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 improper management. 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.

Effect of In-Season Fertilizer Application on Pressure Flattening Development

Field experiments evaluating calcium, boron, and potassium were designed to include multiple rates and interactions of all three nutrients to improve resistance to pressure flattening. None of the calcium, boron, or potassium treatments had a significant effect on pressure flattening development. It may be that if applications of the nutrients, especially calcium, had been made earlier in the growing season or if the fields had been deficient in those nutrients, the treatments would have had an effect. Further research, especially into the role of calcium applications to reduce pressure flattening, may be conducted using pre-plant applications. Such research should also involve biochemical analysis of cell wall constituents to determine if pressure flattening reduction is due to changes in cell wall composition. It was difficult to determine if the late nitrogen applications resulted in a significant reduction of tuber maturity at harvest. Due to problems with the harvester and the amount of rocks in the soil, it was not possible to accurately determine differences in susceptibility to harvest damage, especially skin durability. For some of the cultivars in the study there was a significant increase in the pressure flattened area per tuber due to additional nitrogen fertilization. It is unclear as to why some of the 22.5 kg. per hectare additional nitrogen treatments resulted in significantly more pressure flattening compared to the 45 kg. per hectare additional treatment. It may be that, for some cultivars, the higher rate resulted in a reaction by the plants that promoted senescence rather than continued growth and tuber bulking. The most promising results for understanding the role of late nitrogen applications in pressure flattening susceptibility were from the experiment that included the slower release organic form of nitrogen and had inorganic nitrogen applied over the foliage. This same methodology was repeated this past year, but at the time this dissertation was being prepared storage samples have yet to be evaluated. As a general statement, the data does suggest that over-fertilization of nitrogen for some cultivars can result in increased pressure flattening during storage. The results of the second year of this study, or future research, will likely determine if the increases in pressure flattening are from moisture loss due to immaturity or other factors.

Evaluation of Post-Season and Storage Methods to Reduce Pressure Flattening.

Effect of Moisture Loss Treatments on Pressure Flattening

Differences in pressure flattening development occurred within a cultivar as a result of moisture loss treatments as well as among the cultivars. There was no difference in the storage time required for Centennial Russet to pressure flatten beyond USDA grade tolerances when the tubers had five percent (4.99%) or less than one percent(0.52%) weight loss prior to storage. Russet Norkotah tubers that lost less than one percent (0.37%) weight could be stored six additional weeks before the tubers were out-of-grade compared to those that lost nearly four percent weight (3.82%). As tuber moisture loss increases, including loss during the storage season, cellular turgor decreases resulting in reduced mechanical resistance of the tissues (Alvarez and Canet, 2000). The oven dry potatoes were not affected by treatment in such a way that tubers were prone to differentially higher moisture loss during the subsequent storage period for Rio Grande Russet, Canela Russet and Russet Norkotah. This lack of difference in moisture loss during subsequent storage indicates that the oven moisture loss treatment did not affect tuber respiration and dormancy. Centennial Russet tubers lost significantly more weight during storage among the oven dried potatoes compared to air dried potatoes, but there was no significant difference in pressure flattening development between air and oven dried treatments. However, the results confirm that reduced tuber turgidity as a result of loss of moisture, caused tissue to be more susceptible to deformation in some cultivars. When the cultivar results were averaged, there were significant increases in the number of flattened areas and the combined flattened area per tuber when samples were oven dried. There are important economic implications of reduced at- harvest moisture loss for potato production and storage management. Some cultivars such as Russet Norkotah may be profitably packed and sold for longer durations if moisture loss at harvest and early in the storage season is kept to a minimum. For other cultivars, such as Canela Russet, storage of potatoes in piles that are 5 meters or more in height may make economic sense only for short durations of storage, even if moisture loss can be minimized

At harvest texture analysis from different fields within the same cultivar may allow for identification of potato storage sections that are more susceptible to pressure flattening due to moisture loss. These potatoes could then be sold and shipped earlier in the season before their value decreases precipitously.

The Effect of Post-Vine Kill Irrigation on Pressure Flattening Development.

It was anticipated that post vine kill irrigation would reduce pressure flattening after storage. However, the opposite trend was observed. In the first year of experimentation, after 6 months storage duration, the potatoes that received 1.2 cm. supplemental irrigation had more pressure flattened are compared to the control. In the second year (2011-2012), results appeared more mixed with Rio Grande Russet and Colorado Rose showing a trend towards increased pressure flattening as a result of the additional irrigation and Canela Russet showing a decrease in pressure flattening from supplemental irrigation (Canela Russet). A potential cause of these findings would be that the irrigation treatment the first year resulted in a soil moisture content that may have been higher than optimal resulting in delayed tuber maturity and skin set or causing hypoxic conditions for the tubers. There is also a potential that tuber tissue at higher turgor, while more elastic, is more prone to deformation during storage (Mayora et al. 2007). Soil moisture content was generally lower during the second year of experimentation. This may have resulted in soil moisture content under irrigated treatments being more optimal for turgor and maturation of some cultivars, while still being too wet for other cultivars to mature. Upon hindsight, it may be that more effective experimentation could have been acheived by applying irrigation when necessary to achieve differences in soil moisture content rather than evaluating irrigation events that are applied without regard to soil moisture content. It appears that there is a cultivar specific optimal soil moisture content, above which tubers may be stressed or fail to mature (resulting in increased pressure flattening susceptibility) and below which tuber maturation may also be delayed and tuber dehydration may occur (resulting in increased pressure flattening susceptibility).

The Role of Pile Height and Storage Duration on Pressure Flattening Development.

The initial results of the pile height evaluation experiment indicate that pile height changes of less than 1 m. can result in significant differences in pressure flattening after 3 months storage duration. Further analysis of the data indicated that there may be differences among cultivars in how much pressure flattening increases as pile height is increased (data not shown). This experimentation is in the initial phase of a two to three year study to determine the effects of pile height and to develop cultivar specific pile height recommendations for Colorado potato growers. The experimental data may change the economic calculations made by growers when trying to decide between piling potatoes higher to reduce storage related expenses and reducing pile height to avoid pressure flattening losses. Based on the initial data it could be recommended that growers should store higher value potatoes, such as red skinned potatoes at 3.6 m. or less pile height if the potatoes are likely to be stored for more than 3 or 4 months. An exception to this recommendation would be if the storage operator has previous experience that indicates that a particular cultivar will store well at longer storage durations or at greater pile heights.

When the development of pressure flattening across multiple fields and cultivars was averaged for the last 3 years, it appears that after the first few months of storage there is a continuous linear increase in pressure flattened area, especially between 3 and 6 months storage duration. With regard to the number of pressure flattened areas it is likely that after 5 months of storage, the number of areas of contact with adjacent tubers that will result in pressure flattening is determined. Based on the data from the past few years it appears that after 3 months of storage duration, pressure flattening will increase continuously for tubers in the lower half of a pile of bulk stored potatoes. Further evaluation of the data is currently being performed to develop an equation, based on multi-year data, for the rate of daily pressure flattening increase after three months storage. This should enable different treatments or cultivars to be evaluated based on how many additional weeks or months of storage can be obtained before the pressure flattened area is equal to the area produced using current cultivars or practices.

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