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Grant Project Final Report

Contract Number: 20025

Grant Project Title: Improving the Fry Color of Processed Potato in Wisconsin

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Agricultural Diversity and Development Program, WPVGA Subcontract

Project Title: **Improving fry color of processed potato in Wisconsin**

Agency project number: 20025 UW Project No. 133-HX85

Final Report: 6/1/07

Project Director: Mike Carter

Project Objectives

The goal of this research and demonstration project is to develop and promote improved management of processing potato for improved sugar concentrations and better fry color.

1. Quantify the interaction of chemical maturity and vine kill timing on the reducing sugar concentration of the stem and bud ends of Russet potatoes from vine kill until harvest.
2. Determine the optimal preconditioning practices (temperature and duration) to minimize reducing sugar levels in the stem and bud ends of russet potatoes subject to different vine kill timings and chemical maturity levels.
3. Quantify and demonstrate the influence of irrigation management and intermittent drought stress on the fry quality of processing potato

Objective 1.

Research related to objective 1 was completed and summarized during the 2006 growing season. The manuscript resulting from this research has been accepted for publication in the American Journal of Potato Research and the final draft of the document is attached. We are working with Paul Bethke and Jed Colquhoun in the Department of Horticulture to continue these efforts under separate funding during 2007. We have also received funding from the WPVGA to address questions related to chemical maturity in chipping potatoes.

We have used results from this research and related projects to develop an extension bulletin which is nearing publication. Current draft is attached and will be distributed to all potato growers in Wisconsin. Results of this research are also being incorporated in variety specific management recommendations for Millennium Russet and Defender. I presented information related to this research at the McCain agronomy meeting during the last week of March. Nearly all of the processing potato growers in Wisconsin were present at the meeting.

Findings indicate the Russet Burbank potato quickly increases sugar concentrations after reaching chemical maturity in late August. The sugar concentrations continue to increase after potatoes are placed into storage. In addition, when potatoes reach chemical maturity they stop bulking. This typically occurred prior to vine desiccation.

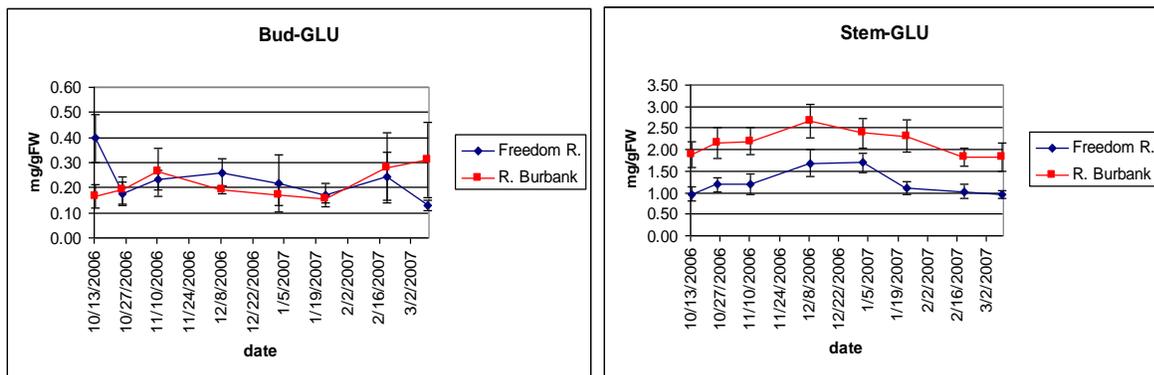
Objective 2.

We have placed Russet Burbank and Freedom Russet potatoes into the Potato Storage Research Facility at Hancock, WI, following harvest in September. Potatoes were collected from common treatments within a common field experiment conducted during the 2006 growing season. We have been holding the potatoes at 55 F, the common preconditioning temperature for potatoes. Every other week six tubers are collected from four different replications. Tubers are sampled for sugar concentrations in the bud and stem end. Sucrose and glucose levels have held steady for the project duration on the stem end while they have decreased on the bud end (Figure 1). Bud end sugars are lower in Russet Burbank than previously witnessed, but are twice the acceptable level for frying on the stem end. The last sampling will occur in June 2007 and then the potatoes will be discarded.

This research will continue in 2007 and 2008 storage season with focus on Bannock Russet and Freedom Russet potatoes. In addition, commercial scale storage research trials will be conducted to determine feasibility of long-term storage of each variety. Freedom Russet consistently has lower glucose content in the stem end of tubers and results in improved fry color upon processing (Figure 1). Bannock Russet also has lower sugar concentrations compared to Russet Burbank and also has improved tolerance to early dying and lower nitrogen fertilizer requirements.

Conclusions to date suggest that storage sugars are highly influenced by field management and growing conditions. Improvements in fry color of Russet Burbank potatoes will require optimal irrigation management. In addition, alternative management strategies such as green digging or changes in varieties may have to be considered to improve sugars in the Wisconsin processing potato crop.

Figure 1. Bud and stem end glucose concentration in Freedom and Burbank tubers held



in storage at 55F.

Objective 3.

Field scale and small plot experiments have been conducted as part of this research trial. The small plot trial was conducted at the Hancock Agricultural Research Station during 2006. The design of the experiment was modified slightly based on input from interested potato growers. Irrigation frequency was the whole plot, with half of the treatments being irrigated daily, while the remainder of the treatments was irrigated every other day. In addition, we compared deep planting potato into flat hills with the conventional hill shape and planting date utilized at by much of the potato industry. The goal of deeper planting into a flat hill was to reduce soil temperatures and thereby reduce a major stress influencing sugar end defect. Finally, we varied nitrogen application timing. Plots were either fertilized at the standard timing during crop emergence and hilling or spread out over the growing season.

Within the small plot experiment we monitored soil moisture and temperature in the tuber zone. Tubers were sampled every other week from the beginning of August until the vine kill for stem and bud end sugar concentrations and then again at harvest. Finally, tubers were placed into storage from each treatment after grading and held at 57 F for 6 weeks before being lowered to the set point at 47 F. Tubers were sampled for sugar concentration out of storage at 47 F in March. This experiment will be repeated during the 2007 growing season.

Field scale demonstration trials were conducted in collaboration with Coloma Farms. Coloma Farms irrigated processing potatoes with the increased frequency approach described in the small plot study. Tuber quality is being evaluated in response to treatments. We are planning to evaluate several processing russet fields the coming summer. The focus will be on identifying fields with historical superior or inferior quality. Fields will be identified with the assistance of McCain Foods. Soil moisture will be monitored by McCain Foods. Tuber bulking, chemical maturity, and sugars out of maturity will be tracked in each field.

Outreach

Several aspects of research conducted under objectives 1 and 2 have been presented at extension meetings in Stevens Point. Sugar storage profiles developed in Objective 2 were discussed at the Annual Potato Grower Education Conference in Stevens Point in February. Further information will be made available through field days, publications, and winter meetings as data is completed.

Importance of Tuber Maturation for Improving Potato Storability

Optimizing skin-set, sugars, and solids

Alvin J. Bussan, Robert P. Sabba, and Michael J. Drilias, University of Wisconsin-Madison, Department of Horticulture

Farmers in Wisconsin typically produce over 30 million cwt (hundred weight) of potatoes annually. Wisconsin potatoes are sold for fresh market, processing, chips, and seed. The WI potato crop is stored in climate controlled warehouses to allow for a steady supply of raw product all 12 months of the year.

The farm gate value of the WI potato crop exceeds \$200 million annually. The impact of potato on the state economy increases when considering the value added by processing potatoes in packing sheds, French fry, chip, dehydration and other plants. Storage of potatoes increases the operational season of processing plants in the state.

Annually, 75 to 80% of Wisconsin potatoes are stored. Storages owned and operated by potato farmers or processing companies have a raw product value of \$160 million. Each commercial storage unit may hold between 30,000 and 100,000 cwt of potato. Storage breakdown during 2000 and 2001 resulted in greater than 20% loss of the stored crop, costing Wisconsin potato farmers an estimated \$32 million. Even during good storage years, storage losses are estimated at 10%.

Maximizing the value of the stored potato crop in Wisconsin requires careful management of the crop going into storage. The value of stored potatoes can be increased by preventing tuber losses and maximizing tuber quality in storage.

Storage losses result from tuber shrinkage and spoilage. Shrinkage is the loss of moisture and carbon from the tubers via evaporation and/or respiration. Spoilage is the breakdown of tubers by pathogens once potatoes are in the storage. Tuber diseases can spread quickly within a potato pile and can cause catastrophic losses.

Storage losses also results from rejection of potato by processors due to losses in storage quality. Quality factors of the stored potato crop differ with end use. Fresh market quality factors include bruise and surface blemishes. Processing and chip quality factors include solid content, bruise, and fry or chip color. Seed quality factors include sprouting, presence of disease on tuber surfaces, and bruise. Good storability equates to potatoes with good quality going into and coming out of storage.

A key to maximizing storability is harvesting a healthy and high quality crop. Potato tuber maturation is necessary to ensure potato crop health in storage. Potato maturation refers to several distinct processes that occur as the crop approaches harvest (Table 1). These aspects of maturity are defined below, and management principles are described that will increase the likelihood of producing a crop with good storability.

Table 1. Aspects of potato maturity that effect tuber storability and quality.

	Vine maturity	Chemical maturity	Physiological maturity	Physical maturity
Characteristics	Senescence of leaves	Low tuber sucrose	High specific gravity	Skin set
Benefits	Allows for tuber maturity and better tuber storage	Better chip and fry color	High yields and better quality	Minimizes skinning, shrink and disease
Management	Decrease availability of nutrients and water late in the growing season. Desiccate vines 2-3 weeks prior to harvest.	Monitor sucrose content before and after vine kill. Harvest tubers when sucrose is at a minimum.	Monitor specific gravity before harvest. Harvest when specific gravity is high.	Desiccate vines 2-3 weeks prior to harvest. Confirm sufficient skin set prior to harvest

Potato Vine Maturation

Vine maturation occurs over the final two to three weeks of potato plant growth. Ideally this corresponds with the final two to three weeks of the production season to allow for optimal crop yield and quality. During plant maturation, the potato canopy begins to senesce, photosynthesis decreases, and the movement of carbohydrates to the tubers declines. At this time tuber bulking and growth rates decrease. This is beneficial, since it is a requirement for tuber maturation to occur.

Potato farmers can stimulate tuber maturation by desiccating vines with non-selective contact herbicides. Delaying potato vine maturation with intensive nutrient, pest, and irrigation management increased tuber bulking and tuber size. However, delaying vine maturation can make desiccation difficult and likely delay chemical maturity and skin set and lead to reduced storability.

A key change in WI potato crops over recent years has been implementation of field management strategies that increased the vigor of vines prior to desiccation in the middle of September. In years prior to the use of these strategies, Russet Burbank potato vines senesced prior to application of vine desiccants. However, recent advances in management of early blight and aggressive early dying management allowed Wisconsin potato growers to maintain vigorous vines well into September. As a result, the maturation process of potato does not initiate until vine desiccation. Potato tubers require up to 40 days for maturation. Recent production practices in Wisconsin have tried to squeeze maturation into a 3 to 4 week window (20 to 30 days).

Potato Tuber Maturity

Tuber maturity refers to chemical, physiological or physical maturity. Each of these maturity categories reflects a different process that occurs in the potato plant. Each maturity category has a different impact on the storage quality of the crop, or the ability of the tubers to withstand losses. Tubers that are chemically, physiologically and physically mature are most likely to have excellent storability.

This bulletin will define the process of chemical, physiological, and physical maturity and how to monitor each. Consequences of failing to mature the potato crop will be explained as well. Finally, management steps that promote the maturation of tubers will be provided.

Chemical Maturity

Process. Chemical maturity refers to the sucrose content within tuber tissues. The extent of chemical maturity reflects the movement of sucrose within the plant during the course of the growing season. Sucrose is of critical importance because it is the primary carbohydrate translocated from the leaves to the tubers. Sucrose is converted to starch, the primary storage carbohydrate in potato tubers, upon entry into the tubers of growing plants.

Shortly after tuber initiation, starch synthesis and accumulation begins within the tuber. Sucrose translocated from the leaves to the tuber quickly enters the starch synthesis pathway and little free glucose or fructose is formed. As a result, the glucose and fructose content declines quickly to a minimal level during early growth of the tubers.

As the potato plant matures, the vines begin to senesce and photosynthesis declines. This leads to reduced movement of sucrose to the tubers. As the tubers mature, the sucrose concentration approaches minimal levels as it is quickly converted to starch upon entry into the tuber. Chemical maturity is achieved once sucrose concentrations reach a minimum. The sucrose concentration at chemical maturity is typically less than 1.0 mg/g fresh tuber weight for processing and chipping potatoes intended for long-term storage.

Tubers harvested during late bulking or during maturation typically have low glucose or fructose concentrations. These potatoes will generally have good fry color due to low reducing sugar content irregardless of sucrose concentration if processed directly from the field. Conversely, once tubers are in storage or subjected to stress events, sucrose is more likely to be converted into reducing sugars glucose and fructose. Accumulation of reducing sugars during storage will lead to poor fry color.

Inset:

Sugars of concern within potato tubers include glucose, fructose, and sucrose. Glucose and fructose are reducing sugars. Reducing sugars react with free amino acids during frying to produce a brown to black darkening of tuber tissue. The dark color is correlated with reducing sugar concentration in the tuber and is undesirable in the chip and French fry industry. Sucrose is a non-reducing sugar and elevated concentrations do not immediately result in dark fry color. Once in the tuber, sucrose is either used to make starch or broken down to glucose and fructose. During plant growth and tuber bulking, sucrose is typically converted to starch. In storage, the breakdown of high sucrose contents can result in elevated reducing sugars that produce dark coloration upon frying. High sucrose can result from harvesting chemically immature tubers or breakdown of starch.

Consequences of failing to chemically mature potato. Tubers harvested when chemically immature pose a greater risk of decreased chip or processing potato quality from storage. Chemically immature potatoes will have elevated tuber sucrose concentrations compared to mature tubers when placed into storage. Higher sucrose concentrations could ultimately lead to increased reducing sugar concentrations and darker fry color.

Chemically immature chipping tubers will require longer preconditioning to reduce sucrose levels to low enough concentrations to allow for long term storage. Tuber sucrose concentrations of <1.0 mg/g FW will allow maintenance of low glucose concentrations resulting in acceptable fry color. Preconditioning temperatures for potato are 55 to 57°F. Longer preconditioning periods required by chemically immature potatoes will result in increased shrink (weight loss) and potential for disease development.

Chemically immature chipping potatoes are less tolerant to cold sweetening compared to mature tubers. The set point, or minimum storage temperature, will have to be higher for chemically immature potatoes as a result. Higher set points increase shrink due to increased tuber respiration relative to mature tubers. If chemically immature tubers do develop higher reducing sugars and poor fry color, they will be more difficult to recondition. Finally, chemically immature tubers have shorter potential storage duration as senescent sweetening will begin earlier.

The potential for manipulating tuber sugar concentrations in processing potatoes such as Russet Burbank, Freedom Russet, Bannock Russet, Millennium Russet and others during storage is limited. Preconditioning has smaller effects on tuber sucrose concentrations in russet potatoes compared to chipping potatoes. In addition, preconditioning periods required to decrease sucrose concentrations are much longer in processing russets compared to chipping potatoes, leading to unacceptable losses in shrink and risk of disease development in storage. As a result, elevated sucrose concentrations in processing russets will likely remain higher in tubers harvested immature, leading to higher reducing sugar concentrations and poorer fry color.

In addition, acid invertase activity on the stem end of russet potatoes is typically higher than in the remainder of the potato tuber. The level of acid invertase activity depends on stress experienced during the growing season. Severe cases are called sugar ends as the French fries have a darker fry color on the stem end compared to the bud end of the tuber. The sugars on the stem end of russet potatoes responds little to preconditioning practices in storage.

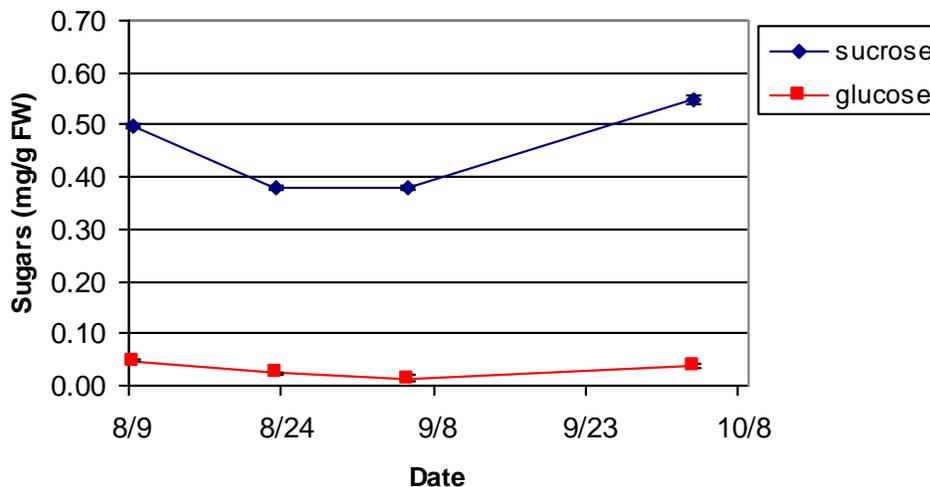
Chemical Maturity Monitoring. Monitoring chemical maturity of chipping potatoes has been common practice for several decades. Chemical maturity is determined by quantifying the sucrose concentration of the potato tubers. Russet potatoes for processing have rarely been monitored for chemical maturity. Chipping potato growers typically begin monitoring sucrose concentrations the first week of August and continue sampling every 7 to 14 days until the crop reaches chemical maturity and is desiccated. Refer to *Maintenance of potato processing quality by chemical maturity monitoring (CMM)* (Minnesota Agric. Exp. Sta. Bulletin No. 5886-1988) for a full disclosure of procedures.

Sampling should be done in at least three to four locations within each field. Each sample should consist of a single mid sized tuber (6 to 10 oz in size) collected from 6 different plants at each location. Tuber samples must be processed within 24 to 48 hours of collection to minimize potential for conversion of sucrose to starch or reducing sugars.

Quantification of sugar concentrations within potato tubers can be accomplished with several methods. The most common method used commercially involves juicing potato tissue and determination of sucrose and glucose concentrations with an YSI 2700 biochemical analyzer (available from Yellow Springs Instruments). Several chipping potato growers have equipment to monitor chemical maturity. In addition, crop consultants will determine tuber sugar concentration for a fee. Techmark, Inc. (<http://www.techmark-inc.com/default.asp> or 517.322.0250) in Michigan is the closest consulting firm to Wisconsin that will process potato tuber samples for sugar concentrations.

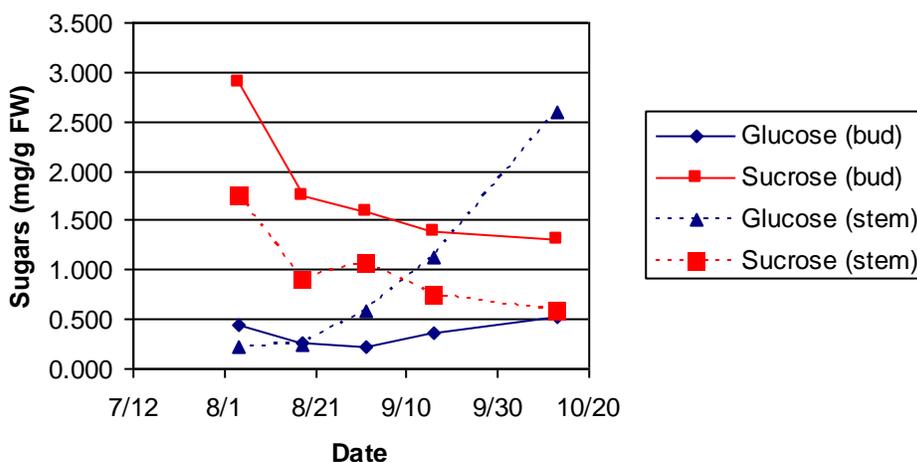
Chemical maturation of chipping potatoes is and should be monitored to minimize tuber sugar concentrations prior to vine desiccation and harvest. Most chip potatoes are chemically mature between mid July and mid-August. Chemical maturity of Dakota Crisp occurred before the end of August in 2006 at Hancock (Figure 1). Sucrose concentrations declined to a minimum and were well below the critical level of 1.0 mg/g FW. In contrast, glucose concentrations were low throughout the entire sampling period up until vine desiccation. Vine desiccation in mid-September and the subsequent harvest triggered increased glucose and sucrose concentrations in early October. These sugars are typically reduced through preconditioning to allow for acceptable chip color out of storage.

Figure 1. Sucrose and glucose concentrations in Dakota Crisp tubers sampled directly from the field during August through September. Vine desiccant was applied 9/16.



Chemical maturity of processing russets is rarely monitored by commercial growers. Sugar concentrations of bud and stem end of russet and other long tubers are typically quite different, so sugar concentrations must be monitored separately (Figure 2). Sucrose concentrations of Russet Burbank were minimized by early to mid September in both ends of the tuber with concentrations being higher in the bud end. Glucose concentrations were minimized up until chemical maturity. However, glucose concentrations increased in the stem end of the tuber from the time of chemical maturity until harvest. Drought and moisture stress can result in increased acid invertase activity leading to conversion of sucrose to reducing sugars once tubers reach chemical maturity. Unfortunately, glucose accumulated in the stem end cannot be reduced through preconditioning.

Figure 2. Sucrose and glucose concentration in bud and stem end of Russet Burbank tubers sampled directly from the field during August through September.



Management of chemical maturity. Chemical maturity management is critical in chipping potatoes to insure minimal tuber sucrose concentrations upon harvest and allow for management of reducing sugars and optimization of chip color. Chemical maturity management in processing russet potatoes is more difficult due to accumulation of reducing sugars in the stem end of potato and apparent influence of crop growing conditions on tuber sugar concentrations.

Chemical maturity is managed by allowing the crop to mature. Chipping potatoes should be monitored for sucrose to make sure concentrations are minimized below 1.0 mg/g FW for Snowden and other varieties. Varieties differ in sucrose concentrations at chemical maturity. Some new varieties are not chemically mature until sucrose levels are reduced below 0.7 mg/g FW or lower.

Insert: New potato varieties such as Premier or designated as LS have much higher sucrose concentrations at chemical maturity and harvest than traditional varieties such as Snowden. As a result, optimal sucrose concentrations at vine desiccation and harvest will differ relative to currently produced varieties.

Vine desiccants should be applied after potatoes are chemically mature and when tubers have finished bulking to optimize yield and minimize tuber sugar concentrations prior to harvest and placement in storage. Vine killing can lead to increased tuber sucrose concentrations following application and prior to harvest. Reducing sugars accumulated during this time are easier to metabolize during preconditioning in chemically mature tubers than in immature tubers.

Practices that delay crop maturity will delay chemical maturity and increase tuber sucrose concentrations in storage. Excess nitrogen can lead to increased vine growth and delayed tuber bulking and ultimately higher tuber

sucrose concentrations. Final nitrogen applications should be made within 80 to 85 d of crop emergence or at least 30 d prior to vine desiccation. No yield or quality benefits have been observed when nitrogen has been applied later than 45 d before vine-kill.

Irrigation can also influence chemical maturity. Less frequent and more thorough irrigation 15 to 30 days prior to vine desiccation promotes tuber bulking and chemical maturation under good growing conditions. If conditions become hot and lead to soils warmer than 75 F, more frequent irrigation may be necessary to reduce hill temperature and maintain tuber bulking. Allow vines to senesce naturally to promote tuber bulking.

Preventing over maturation can be just as important as managing for chemical maturity. Over maturation leads to elevated sugars as well. Premature vine death due to inadequate fertilization, drought stress, or early dying can result in over maturation of potato tubers and increased tuber sucrose levels. Long delays in harvest following vine-desiccation can also lead to increased sugar concentrations especially if low temperatures approach freezing. Over mature potatoes should be chipped or processed as soon as possible as they will have limited storage duration.

Physiological Maturity

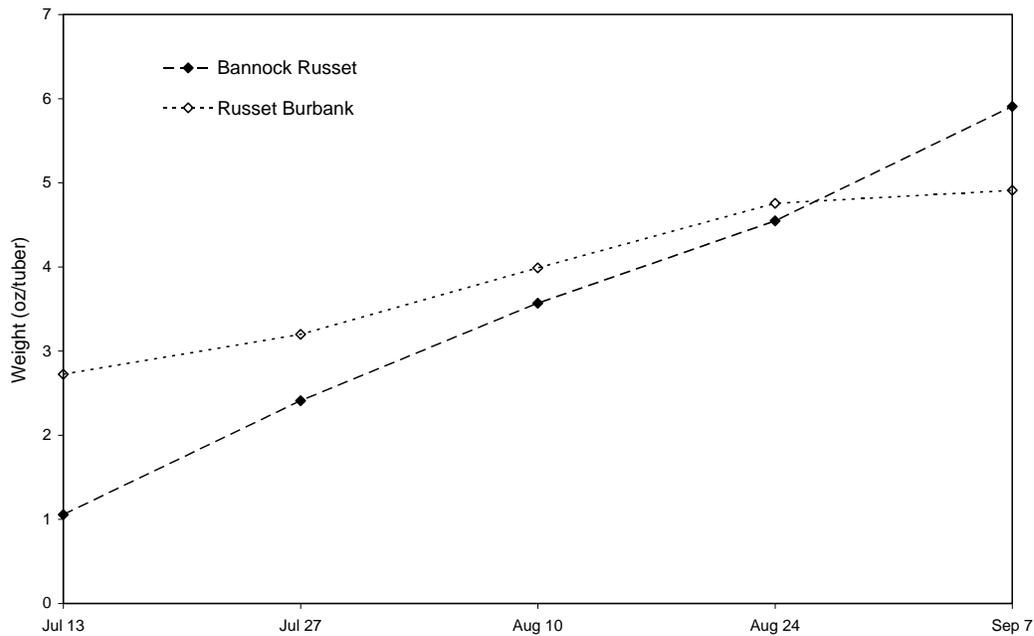
Process. Physiological maturity refers to the state of the dry matter content of the potato tubers. Starch is the primary storage carbohydrate in potato tubers. Potatoes with high starch and low sucrose content generally have better processing characteristics and better attributes for fresh market potatoes. Starch and dry matter content reach a maximum as potato tubers mature. Correspondingly the specific gravity will reach a maximum as potatoes mature. A majority of sucrose is converted to starch or respired in the tubers during maturation until maximum solid content is reached.

Consequences of failing to physiologically mature potato. Harvesting potatoes before they reach physiological maturity will result in loss of yield due to unfulfilled tuber bulking. In addition physiologically immature potatoes will have reduced solid content leading to reduced specific gravity. Lower solids results in poor processing quality and reduced prices if specific gravity does not meet minimum contract requirements. Lower specific gravities results in poorer end product quality as well.

Monitoring physiological maturity. Monitoring physiological maturity requires determination of tuber specific gravity. Determine specific gravity every 7 to 10 days until tubers reach a maximum or at the very least the minimum level specified by contract. Russet Burbank reach maximum tuber size by the end of August while Bannock Russet continued bulking into September (Figure 3).

Figure 3. Average tuber size of Russet Burbank and Bannock Russet potatoes sampled from the field during July through mid September during 2005.

Tuber bulking in russet processing potatoes - 2005



Correspondingly, Millennium Russet had maximum tuber specific gravity by the end of August, but Russet Burbank did not reach maximum specific gravity until September suggesting later physiological maturity (Figure 4).

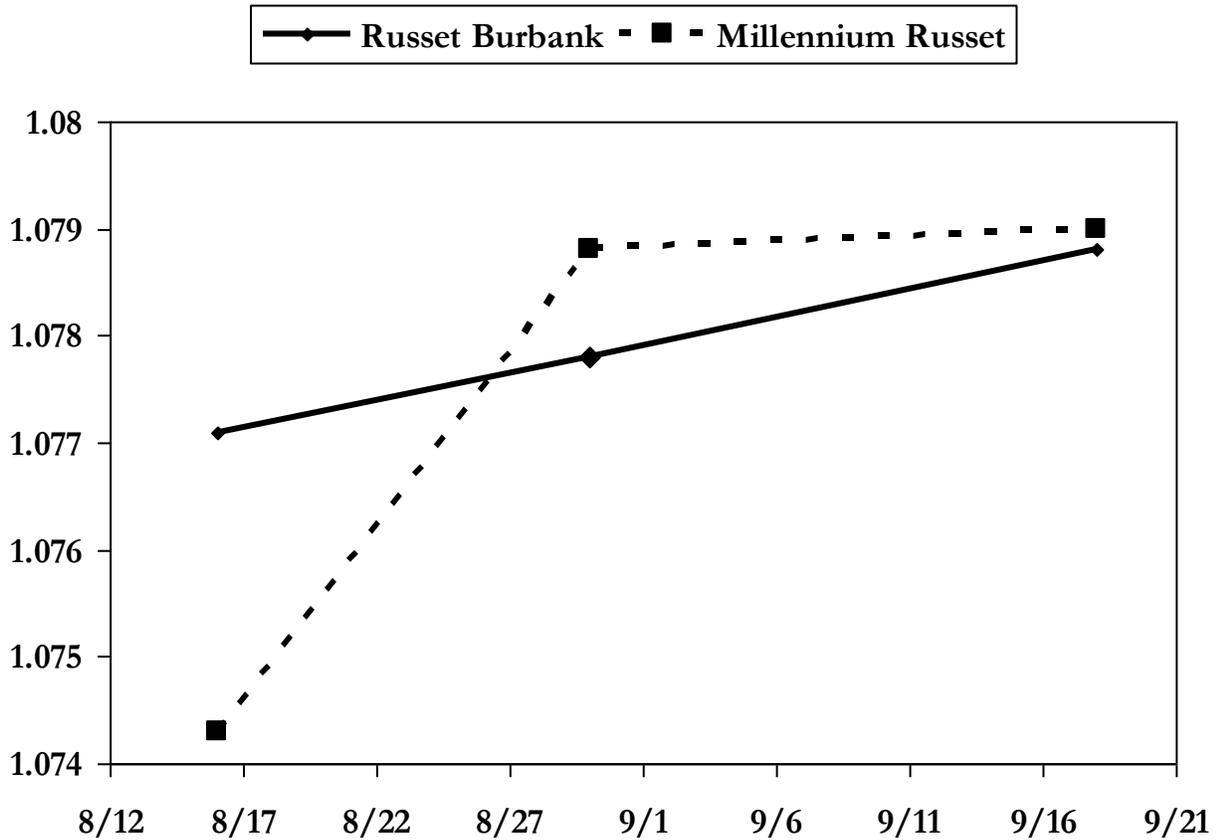
Several methods are available for determining tuber specific gravity. Hydrometers are available from multiple sources. Suspend predetermined weight of potato tubers in a basket and suspend from the hydrometer in water. The specific gravity is determined by estimating the level of the water on the scale. Hydrometers must be calibrated to accurately predict tuber specific gravity.

Alternatively, specific gravity can be determined by measuring the weight of potato tubers in air and in water. Specific gravity is calculated by:

$$\text{Specific Gravity} = \text{Weight in air} / (\text{Weight in air} - \text{Weight in water})$$

Automated systems are available for determining specific gravity at the Hancock Agricultural Research Station and on several other farms.

Figure 4. Effect of vine-kill timing on specific gravity of Russet Burbank and Millennium Russet Potato. *Managing for physiological maturity.* Managing for physiological maturity simply requires allowing the crop to



mature. Delayed crop maturation due to excess nitrogen application can prevent physiological maturity and result in decreased specific gravity. Vine desiccation can promote physiological maturity and result in slight increases in specific gravity.

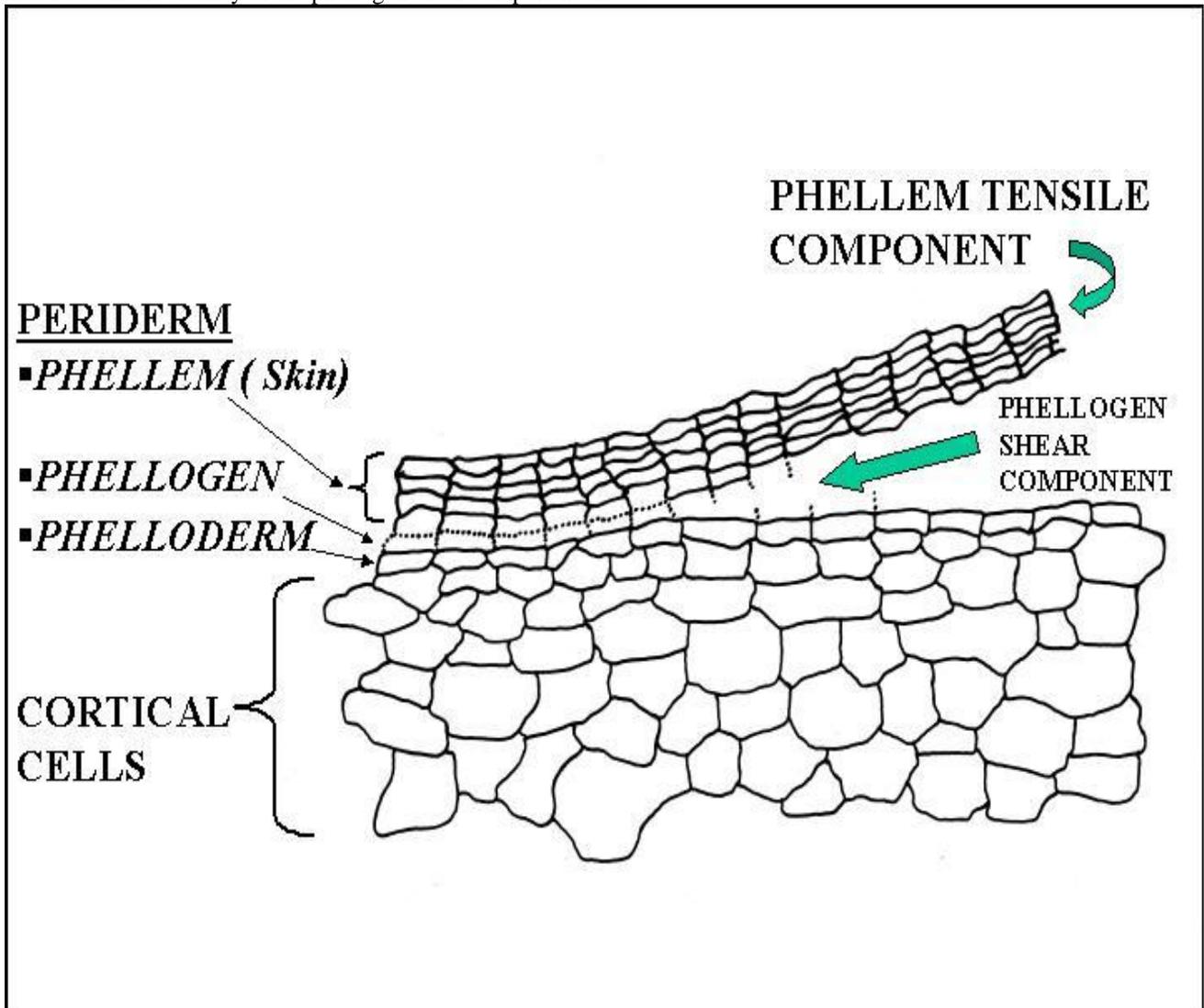
Physical Maturity – SKIN SET

Process. Physical maturity relates to skin set on potato tubers. Skin-set refers to the resistance to skinning injury. Potato tubers expand rapidly during late tuber bulking. The skin which is part of the periderm, must be capable of expanding with the growing tuber. As the crop starts to mature, potato tubers stop expanding and the skin starts to set. Skin set is a key process of potato maturation and is important for protecting the tuber from damage during harvest, handling, and in storage. Skin set typically requires 40 days, but most crops are harvested within 20 days of vine kill.

The periderm is composed of three layers of tissue, the phellem, phellogen, and the phelloderm (Figure 5). The phellem is the outer tissue and is referred to as the skin. The phellogen is a thin region of immature, meristematic tissue (rapidly dividing cells). The phelloderm is the tissue adjacent to the starch-storing cortical tissue inside the tuber.

Figure 5. A diagram of the potato periderm showing the phellem, phellogen, and phelloderm and underlying cortical cells. Skinning occurs when physical forces cause phellogen cells to break and the phellem to peel off, as

illustrated in the vicinity of the phellogen shear component arrow.



From E.C. Lulai (2002) Am. J. Pot. Res. 79: 244. Reprinted with permission.

Production of new cells by the phellogen enables the skin to expand as the tuber grows. These dividing phellogen cells hold the skin in place, but have little strength at this time. The skin of a growing tuber is easily damaged or removed by simply rubbing your fingers over the surface of the tuber (Figure 6).

Figure 6. Skinning injury caused by harvest of immature potatoes.



Skin set provides resistance to skinning and increased resistance to water loss. Skin set and the increased resistance of tuber periderm to skinning is primarily due to strengthening of the phellogen and this occurs over a 2 to 5 week time frame. The cell walls of the phellogen become stronger during maturation and this increases the tuber resistance to physical damage during harvest and in handling (Figure 5). Strengthening of the cell walls of the phellogen is critical as skinning damage is the result of phellogen cell breakage.

Suberin is a complex biopolymer that is integrated into the phellem or skin of the tuber. Waxy materials are embedded into the suberin matrix and restrict water loss through the periderm. Suberin and associated waxes are present in the periderm throughout the growth of the tuber, but the ability of the periderm to minimize water loss increases as the tuber matures. Suberization is also critical for preventing infection of the tubers by fungi and bacteria that cause tuber rot.

Consequences of failing to physically mature potatoes. Physically immature potato tubers are more vulnerable to skinning due to poor or failed skin set. Harvesting potatoes that are physically immature can result in increased damage to the periderm during harvest.

Physically immature potato tubers require longer time in storage to form the closing layer and develop a wound periderm than mature tubers. Increased periderm damage and longer time required for wound healing increases susceptibility of immature tubers to infection by fungi and bacteria once placed in storage relative to mature tubers.

Physically immature tubers have higher respiration rates compared to mature tubers. Higher respiration rates lead to elevated CO_2 and less O_2 within the storage. Higher respiration also generates more heat in the potato pile. Elevated CO_2 and diminished O_2 and warmer temperatures promote development of numerous potato pathogens increasing potential for tuber infections and storage rot or decay. In addition, elevated CO_2 and diminished O_2 inhibit the suberization and formation of closing layers over tuber wounds in storage.

Immature potato tubers have higher evaporative water loss than mature tubers and water loss due to evaporation leads to loss in turgor pressure within cells. Decreased turgor pressure increases tuber vulnerability to damage by pressure bruise. Pressure bruised areas wound-heal poorly, lose further water vapor at the bruise site and frequently develop pressure bruise induced blackening of tuber tissue

Skinned areas heal forming a wound periderm to protect the tuber from infection by bacteria and fungi and prevent loss of water. Wound periderm usually has different coloration than native periderm and little to no russetting. Excessive wounding from skinning injuries of immature tubers will decrease value of fresh market

potatoes due to the influence of appearance on grade. Skinning can cause dark shrunken areas on processing potatoes leading to problems in peeling tubers.

Inset:

Suberin is mainly composed of lignin-like and fatty acid based biopolymers that form a barrier that protects the potato from pathogen attack. Soluble waxes embedded in the suberin network prevent water loss and help the tuber remain turgid. The process by which the potato lays suberin down inside the walls of its cells is called suberization. The phellem (skin) is suberized so as to form a protective barrier around the tuber. When skin is removed from a potato, a wound response results in suberization of the cells underneath the skinned area. This “closing layer” is formed in a few days and provides temporary protection for the tuber. Eventually, a new “wound” periderm is formed underneath the closing layer to provide an organized series of suberized cells, the wound phellem, for permanent protection. Suberization requires oxygen and can be inhibited by anaerobic conditions.

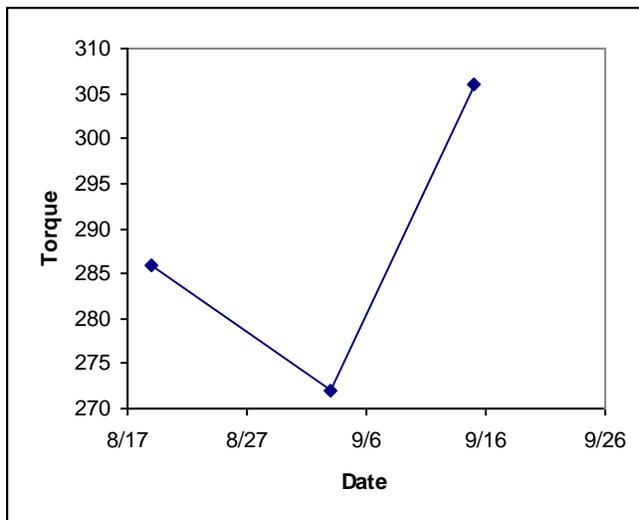
Monitoring physical maturity. Monitoring physical maturity requires determination of force required to remove the potato periderm. Modified torqueometers have been used to quantify skin set in research trials. Physically mature tubers require more torque to remove the periderm than immature tubers. However, torqueometers may not be necessary to determine physical maturity.

Skin set can simply be assessed by using your thumb and trying to remove the periderm. The periderm can be easily sloughed on immature tubers, whereas mature tubers require greater force. Air dry tubers prior to assessing the force required to remove the periderm.

Managing for physical maturity. Physical maturity is managed by vine desiccating potatoes 17 to 21 days prior to harvest. Prevent saturated soil conditions following vine desiccation to minimize free water surrounding tubers. Maintain soil moisture above the critical level to keep tubers hydrated to prevent bruising.

Delaying the date of vine desiccation increased physical maturity and as measured by the force required to remove the periderm (Figure 7). Timing vine desiccation when potato vines have naturally begun to senesce will increase physical maturity. Practices that delay vine senescence such as excess nitrogen or delayed nitrogen application will delay physical maturity and increase susceptibility to skinning.

Figure 7. Torque required to remove tuber periderm of Russet Burbank potatoes at harvest in response to different vine desiccation dates. Tubers were harvested 3 weeks after vine-kill.



Potato types vary in their susceptibility to skinning. Red potatoes are much more vulnerable to skinning than russet or round white potatoes. Red potatoes require a minimum of three weeks after vine killing to set skin.

Some varieties are more vulnerable to skinning as well. Bannock Russet is more vulnerable to skinning than Russet Burbank and Villetta Rose is more vulnerable to skinning than Red Norland.

Potatoes that have been harvested immature and suffered excessive periderm damage will have to be stored to promote wound healing and minimize water loss in storage. Remove field heat as quickly as possible and maintain storage temperature at 55 F to promote wound healing and minimize potential disease development. Air speed should be managed at 1 cfm/cwt to equalize temperature of potatoes within the potato pile and remove free water. Target a Δt (temperature difference between top and bottom of the pile) of 1 to 2 F to equalize the pile.

Maintain humidity at 95% to minimize water loss from tubers and potential for pressure bruise. The storage atmosphere should be purged with outside air at least once a day to prevent excess CO₂ accumulation in the storage atmosphere. The duration of purging will vary depending on storage volume, air speed and outside versus inside air temperature. Elevated CO₂ delays development of the closing layer and promotes development of anaerobic bacteria that can infect potato tubers and cause decay.

Overall Crop Management

The importance for maturing tubers for optimizing quality of stored potatoes has been demonstrated. The timing of chemical, physiological, and physical maturity is not always coordinated due to slight differences in the processes influencing their development. However, several management factors influence all aspects of tuber maturation and must be implemented for successful long-term storage.

Tuber maturation is linked to the maturation of the entire plant. Managing the crop to keep the vines green and actively growing right up until the time of vine desiccation and harvest will delay the processes of tuber maturation and result in harvest of immature potato tubers. Conversely, if the entire plant matures too early and the vines senesce prematurely then the crop will not reach its yield potential and tubers may become over mature.

The crop must be managed to promote the maturation of the potato plant at the appropriate time. Ideally vines should begin to senesce with older leaves turning chlorotic 14 to 20 days prior to vine killing. This should promote maximum translocation of carbohydrates from the crop canopy to the tuber resulting in maximum specific gravity and yield, and promote the beginning of skin set. In addition, this should reduce the flow of sucrose to the tubers allowing conversion to starch minimizing tuber sugar concentrations.

Crop fertility, specifically nitrogen, has large effects on canopy growth and development. Nitrogen fertilizer rate must be optimized to maximize yield, but excess nitrogen prevented natural senescence of plants leading up to vine desiccation. Nitrogen status within the crop should be monitored with petiole sampling and supplemental fertilizer applied if necessary to ensure crop yield goals are achieved. Supplemental fertilizers should not be applied 80 to 85 d after crop emergence or 40 to 45 d prior to vine desiccation.

Irrigation can also be manipulated to promote natural senescence of vines. During late bulking and plant maturation (late August or early September) irrigation should be less frequent at amounts necessary to re-wet the rooting zone of the soil profile. Irrigation amounts need to be adjusted as vines senesce to reflect the diminishing evapotranspiration by the declining canopy.

Vine desiccation is the obvious and final step for promoting the maturation of potato tubers. Vine desiccants should be applied at least 21 d prior to intended harvest date to promote tuber skin-set and allow maximum specific gravity. Vine desiccation often increases sugar content of tubers, but is necessary to promote skin-set of stored potatoes. In addition, vine desiccation prevents infection of tubers by late blight which is crucial for successful storage. Follow label directions for effective potato vine desiccation.

Vine desiccants vary in their relative activity. Some desiccants kill vines within 12 to 24 hours while others require several days. Research is underway to evaluate the influence of vine desiccant mode of action on the maturation of tubers.

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Figure 1. Sucrose and glucose concentrations in Dakota Crisp tubers from August through September. Vine desiccant was applied 9/16.

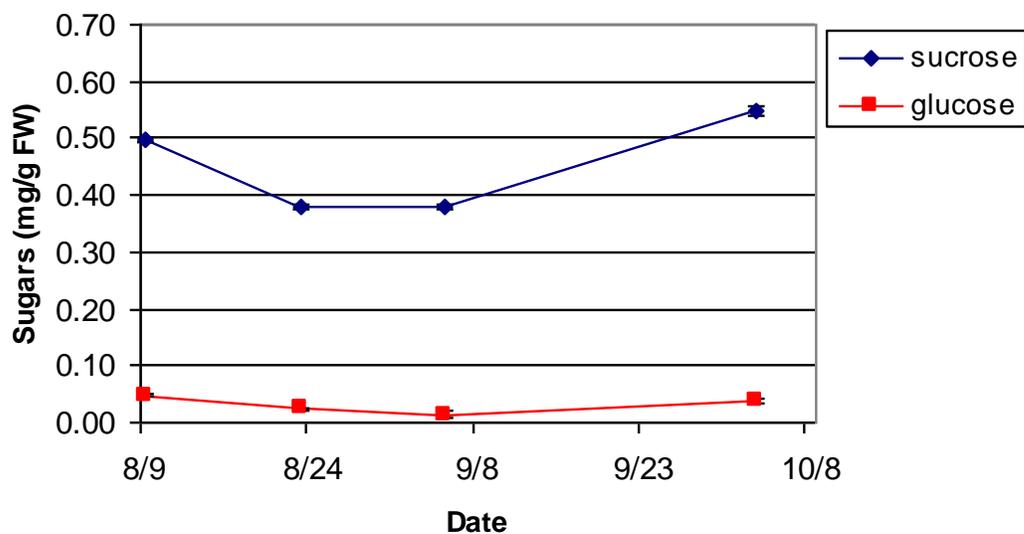


Figure 2. Sucrose and glucose concentration in bud and stem end of Russet Burbank tubers from August through September.

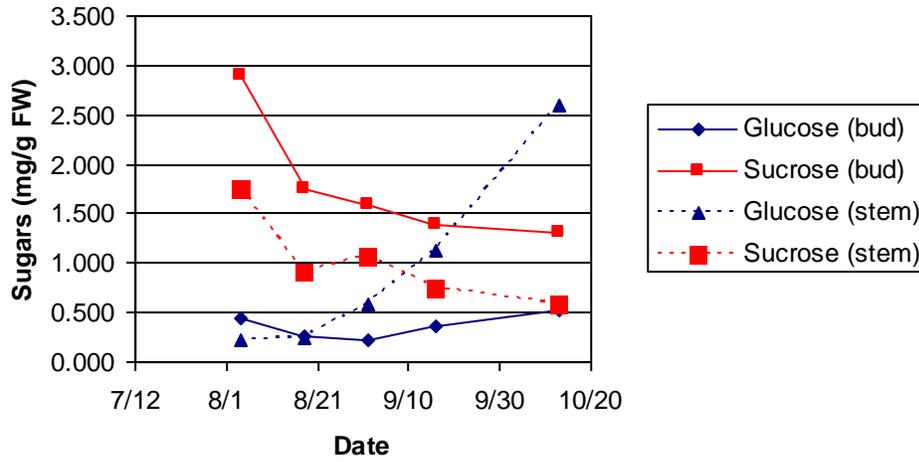


Figure 3. Average tuber size of Russet Burbank and Bannock Russet from early July through mid September during 2005.

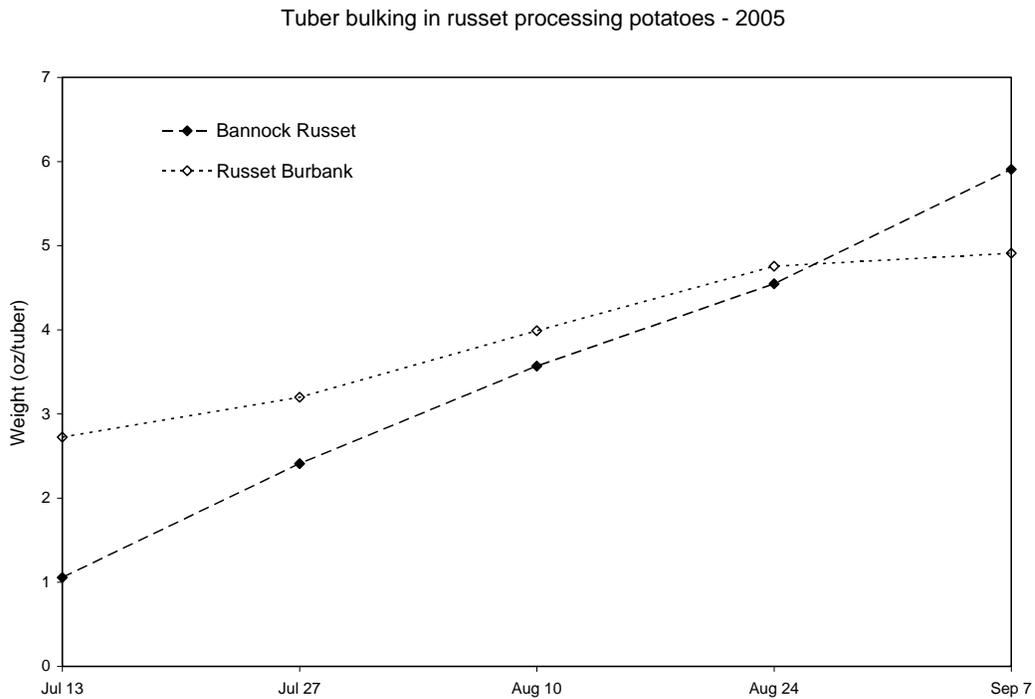


Figure 4. Effect of vine-kill timing on specific gravity of Russet Burbank and Millennium Russet Potato.

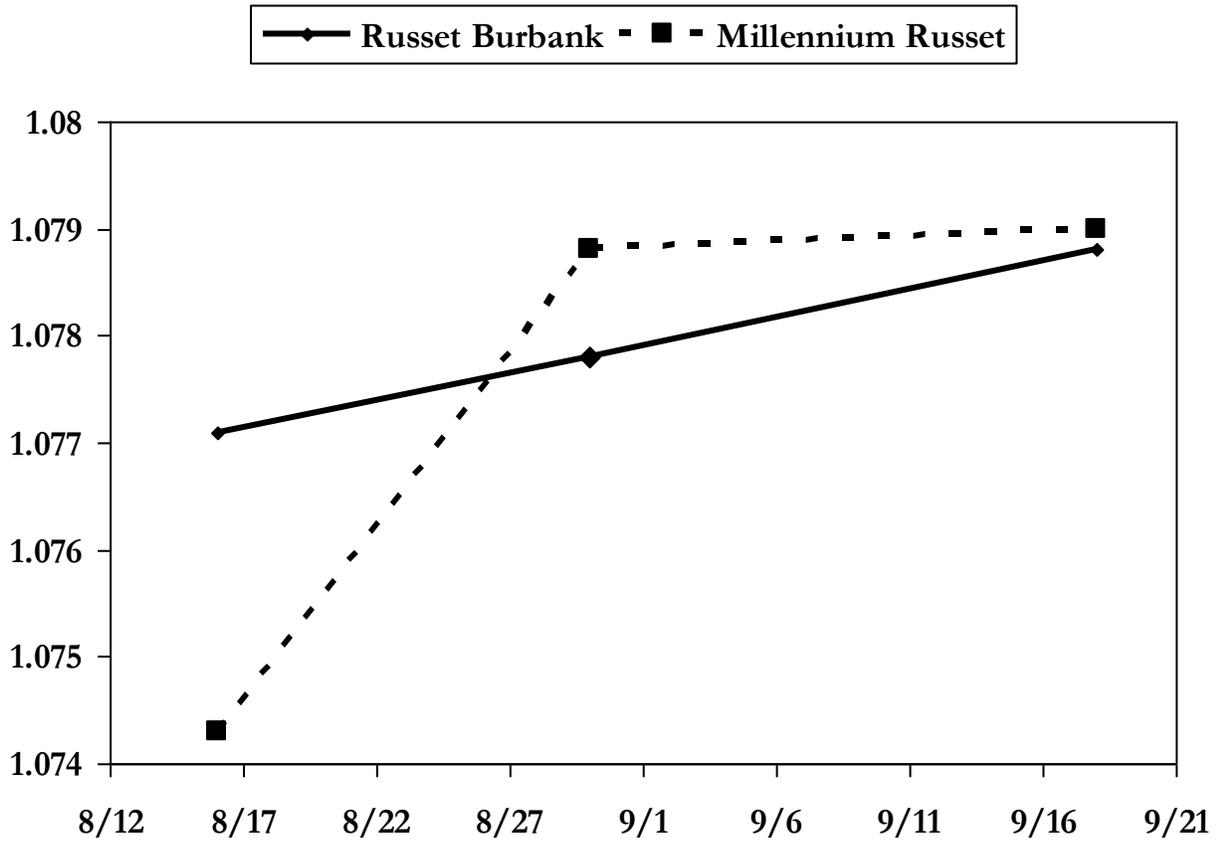


Figure 5. A diagram of the potato periderm showing the phellem, phellogen, and phellogen. Skinning occurs when physical forces cause phellogen cells to break and the phellem to peel off, as illustrated in the vicinity of the arrow.

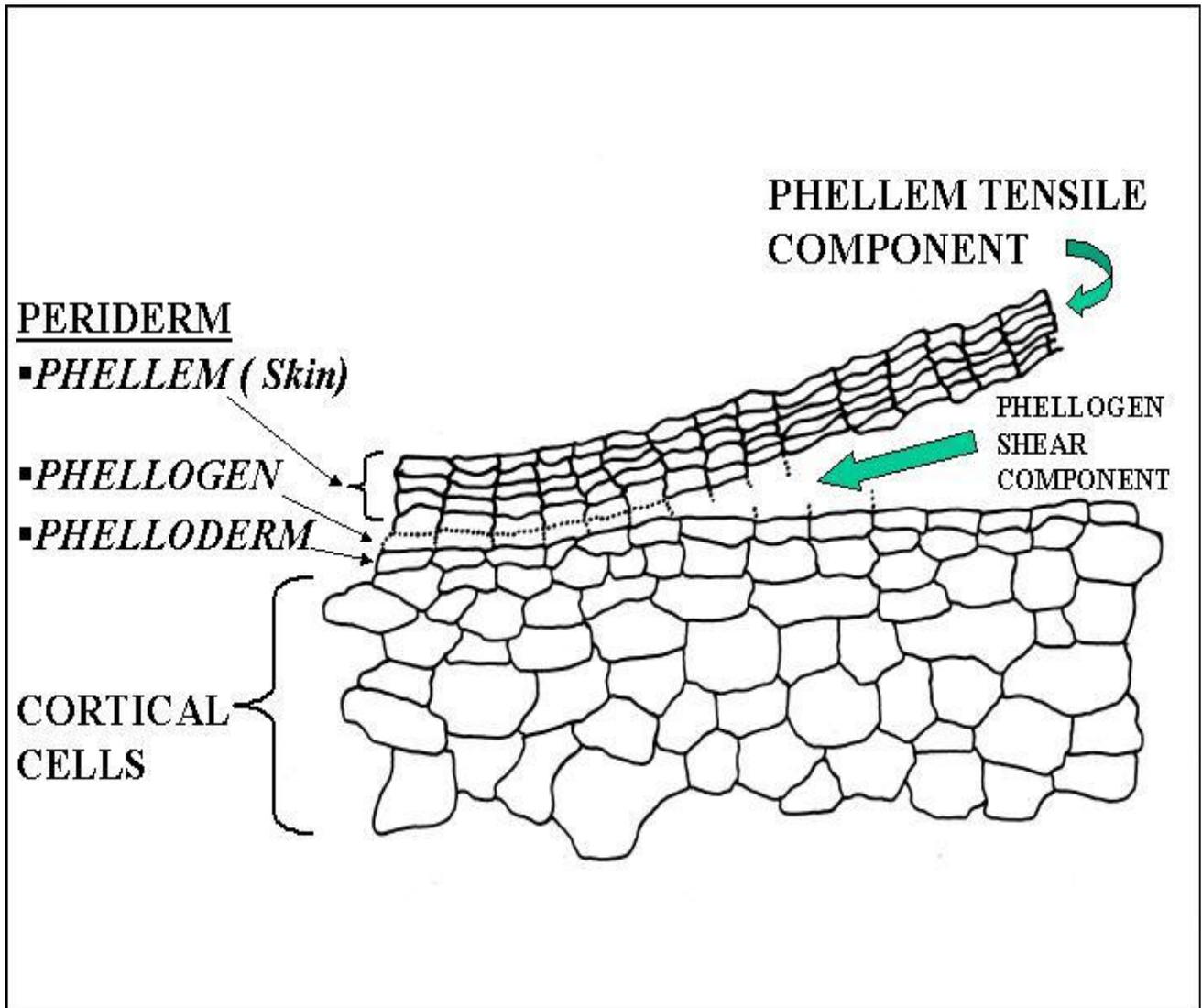
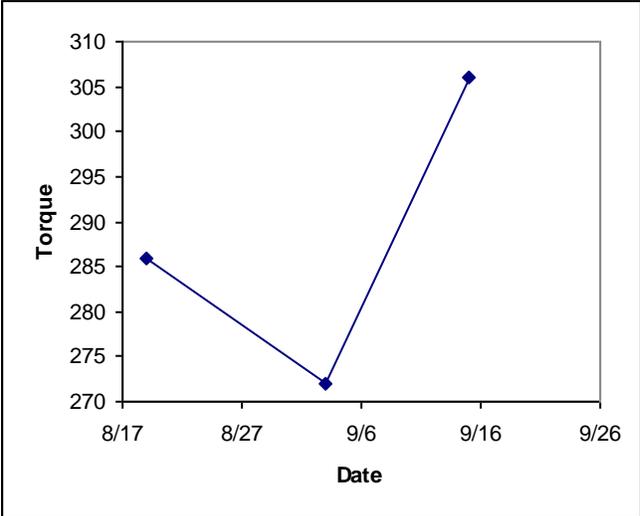


Diagram republished with permission from E.C. Lulai (2002) Am. J. Pot. Res. 79: 241-248

Figure 6. Skinning resulting from the harvest of immature potatoes.



Figure 7. Torque required to remove tuber periderm across different vine desiccation dates.



Effect of Planting and Vine-kill Timing on Sugars, Specific Gravity and Skin-Set in Processing Potato Cultivars

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RUNNING TITLE: PLANTING AND VINE-KILL TIMING ON SUGARS

ABBREVIATIONS: ANOVA, analysis of variance; FW, fresh weight

ABSTRACT

Quality and storability of potato tubers harvested for storage are affected by their chemical, physiological and physical maturity. The sucrose concentration in potato tubers is indicative of the chemical maturity of the crop and of the potential processing quality of the crop after storage. High reducing sugar concentrations result in undesirable discoloration of fried potato products. Sucrose does not directly contribute to the discoloration of tuber tissue upon frying, but influences reducing sugar concentrations during storage. Physiologically mature tubers have maximized their dry matter content resulting in high specific gravities that are desirable for most aspects of potato processing. We examined the effect of different planting and vine-kill dates on the sucrose and glucose concentrations and specific gravity of five processing potato cultivars grown at Hancock, WI, during 2002 and 2003. Although planting date usually had no effect on sugar content at harvest, sucrose and glucose content decreased with earlier planting date at vine-kill in one of two years. Greater sucrose and glucose concentrations and specific gravities were found at harvest with later vine-kill dates. Of particular concern for processing, stem-end glucose concentrations consistently exceeded bud-end glucose concentrations for all cultivars, regardless of the cultural parameters implemented. Physically immature tubers have poor skin-set and are prone to skinning and mechanical damage during harvest, which renders them more vulnerable to dehydration and infection by rotting pathogens in storage. Skin-set of Russet Burbank tubers in 2003 improved with late vine-kill timing. Our data indicate that chemical maturity does not necessarily correlate with either physiological or physical maturity in processing cultivars, rendering the use of cultural practices to improve tuber maturity at harvest problematic.

INTRODUCTION

Potato losses from storage continue to be a serious problem for the potato industry with national losses due to shrinkage and rot exceeding 30 million cwt per year since 2000 (Anonymous, 2004). Crop maturity contributes to tuber storability through improved processing quality and increased resistance to storage diseases. Tuber maturity can be viewed as composed of three components: chemical, physiological and physical maturity (Bussan, 2003).

Chemical maturity refers to the sugar concentration of potatoes. Carbohydrates are supplied to the growing tuber via sucrose which is then converted into starch (Fernie et al, 2002). Sucrose levels are highest in young tubers and reach a low point once the above ground plant enters senescence (Kolbe and Stephan-Beckman, 1997). Tubers are considered chemically mature when sucrose concentrations reach minimum levels and dry matter or starch content reach maximum levels (Iritani and Weller, 1980). Chemically mature tubers typically have lower reducing sugar (glucose and fructose) concentrations during storage (Sowokinos, 1978). Tuber sucrose concentration at maturity is cultivar dependent and can be negatively influenced by a number of factors during the growing season, including heat-stress, water-stress and fertility management (Kumar et al, 2004). Sugar concentrations in stored tubers are also influenced by storage temperatures and duration of storage. Storage at low temperatures inhibits dehydration, sprouting and pathogen growth, but tends to induce the breakdown of starch into reducing sugars (Isherwood, 1973; Sowokinos, 2001). Reducing sugars react with amino acids at high temperatures and produce dark coloration via the Maillard reaction, which is considered undesirable by the chip and fry industries (Shallenberger et al, 1959).

With the exception of Russet Burbank, most research reported on chemical maturity and changes in sugar concentration during tuber growth have focused on round white cultivars primarily used for chipping (Sowokinos, 1971; Iritani and Weller, 1977; Orr et al, 1986; Santerre et al, 1986). Sowokinos (1978) reported that the russet variety Norgold had the tendency toward high sucrose concentrations at harvest and accumulated reducing sugars rapidly during storage compared to round white cultivars. Santerre et al (1986) reported that Russet Burbank took longer to attain chemical maturity compared to several round white chipping cultivars.

Moisture and heat stress during tuber development can lead to an uneven distribution of reducing sugars in the tuber after harvest, referred to as "sugar end," or "translucent end" (Iritani and Weller, 1973; Kincaid et al, 1993). The immediate cause of sugar-end is a shift in the tuber from starch synthesis to starch degradation and increased activity of acid invertase which converts sucrose to the reducing sugars glucose and fructose (Sowokinos et al, 2000). Reducing sugars continue to accumulate and starch breaks down during storage leading to fries that fry dark on one end, and in extreme cases to jelly-end rot. Russet processing cultivars grown in the Wisconsin Central Sands consistently accumulate high levels of glucose at the stem-end after chemical maturity has been attained (Sabba and Bussan, 2005).

Related to chemical maturity is physiological maturity which refers to the percentage of dry matter in the tuber. Physiologically mature tubers have reached maximum dry matter content, which usually coincides with a maximum starch accumulation (Bussan, 2003). Specific gravity is based on dry matter content and is indirectly related to starch content, since 80-85% of the dry matter content of a tuber is composed of starch. High specific gravity is desirable for most cooking purposes, including fry processing (Dean and Thornton, 1992).

Physical maturity refers to skin set and the development of a mature periderm (Wilcockson et al, 1980). Physically mature tubers are resistant to skinning and form wound periderm faster than immature tubers (Lulai and Orr, 1995). Skinned tubers are susceptible to dehydration (shrinkage) and attack by rotting pathogens in storage (Lulai and Orr, 1995; Lulai and Corsini, 1998). Chemical maturity and physical maturity do not necessarily correlate and have seldom been monitored under common experimental conditions.

This research was initiated to determine the effects of planting and vine-kill timing on the concentration of sucrose and glucose and the specific gravity of five processing potato cultivars (Russet Burbank, Millennium Russet, Umatilla, Defender and Shepody). The bud and stem-ends were sampled separately to monitor differences in sugar concentrations longitudinally through the tubers. In addition, skin-set for Russet Burbank was measured in 2003.

MATERIALS AND METHODS

Experimental Design

Potatoes were grown at the University of Wisconsin, Hancock Agricultural Research Station during 2002 and 2003 on a Plainfield loamy sand (85% sand, 8% silt, 7% clay and 0.8% organic matter, pH of 5.8). The previous crop was fallow in 2002 and corn in 2003. The field was moldboard plowed and soil finished with a cultipacker the spring prior to planting, but was not fumigated. Plots were managed following University of Wisconsin

recommendations for fertility, pest and irrigation management. Diquat (6,7-dihydrodipyrido [1,2-a:2',1'-c] pyrazediiium dibromide) was applied prior to harvest at 0.28 kg/ha to desiccate vines. Each experiment was conducted as a randomized complete block with a strip-strip-split-plot factorial treatment design and 4 replications. Strip plot factors were vine-kill and planting dates and sub-sub plot factors were potato cultivar. In 2002, planting dates were spaced ten days apart with the first planting on April 16, 2002 and vine-kill dates on August 14, August 30 and September 18. In 2003, planting dates were spaced 14 days apart with the first planting on April 17, 2003 and vine-kill dates on August 19, September 3 and September 15. Growing days for 2002 ranged from 100 to 155 days across all planting and vine-kill dates. Growing days for 2003 ranged from 96 to 151 days across all planting and vine-kill dates. Cultivars were Russet Burbank, Millennium Russet, Shepody, and Umatilla during 2002. Umatilla was replaced by Defender during 2003.

Sample Collection

Physiological, chemical, and physical maturity of potato tubers was determined by quantifying the specific gravity, glucose and sucrose concentrations, and skin set of tubers, respectively. Tubers were sampled to assess maturity at the time of vine-kill and at harvest. Samples collected at the time of vine-kill were collected from plots established for destructive sampling. At harvest, samples were collected from the center of each plot. In 2002, final harvest samples were collected for every treatment on October 1. In 2003, final harvest samples were collected 3 weeks after the timing of vine-kill to simulate currently recommended best management practices in WI. Samples for determining chemical and physical maturity included six tubers weighing 225 to 340 g from 5 to 6 plants. Physiological maturity was assessed from 7 to 8 kg samples of tubers weighing 200 to 300 g each.

Data Collection and Analysis

Specific gravity was calculated at harvest by comparing the weight of approximately two dozen tubers in water relative to their weight in air (Dean and Thornton, 1992). Glucose and sucrose concentrations were measured utilizing procedures based on Sowokinos et al (2000). The terminal 2.5 to 5 cm on the bud and stem ends of six potatoes from each plot (200g) were juicerized separately with a model 6001 Acme Supreme Juicerator in 50 mM sodium phosphate buffer, pH 7.2. The supernatant solution was brought to a final volume of 275 ml. Glucose and sucrose concentrations of the supernatant were measured with a YSI 2700 select analyzer utilizing grade VII invertase from yeast (Sigma-Aldrich, St. Louis) as per manufacturer's recommendations. A skin-set tester of the type originally developed by Halderson and Henning (1993) and fitted to a Torquometer (Snap-On model TQSI.70 FUA) was used to measure the torque required to excoriate the skin from the tuber surface (Lulai and Orr, 1993). A size 0 rubber stopper was placed at the tip of the skin-tester and pressed against the tuber surface with approximately 25 lbs of force. Skin-set was measured only for Russet Burbank from the 2003 experiment and was conducted three times on three different tubers from each of four replicate plots. Results were analyzed by ANOVA (SAS Institute, Cary) and means separated by main effect (Table 1). Means were separated with Fisher's Protected LSD where appropriate.

RESULTS

Cultivar and vine-kill timing affected sugar levels at vine-killing and harvest and specific gravity at harvest both years (Table 1). Data are presented separately for each year because of differences between sugar levels and specific gravity between 2002 and 2003. In addition, cultivar interactions with planting and vine-kill date occurred within each year. Sugar concentration and specific gravity data for each cultivar are presented across different planting and vine-kill dates each year. Despite the differences in growing days between treatments, there was no planting date x vine-kill date interaction for most data suggesting minimal effect of growing season length.

Sucrose and glucose concentrations in the bud and stem end of tubers differed across cultivars at vine-kill and harvest in both 2002 and 2003 (Table 2). Umatilla and Defender had the highest levels of bud- and stem-end sucrose at vine-kill during 2002 and 2003, respectively, while Millennium Russet consistently had the lowest sucrose levels at vine-kill and harvest. Russet Burbank had the greatest concentration of stem-end glucose at harvest both years, while Umatilla had the lowest in 2002. However, cultivar effects should be evaluated with caution due to interactions with planting and vine-kill timing.

With the exception of stem-end sucrose, both glucose and sucrose concentrations were generally much lower in 2003 compared to 2002 (Table 2). These differences across years may have been due to extended heat stress during the early to mid-bulking stage (from June 15 to July 30) during 2002. Maximum air temperatures

exceeded 30 C for 23 d in 2002 compared to only 8 d in 2003 during the same period (Figure 1, 2). Minimum air temperatures were also warmer during this time period with 10 d exceeding 20 C in 2002 versus 2 d in 2003 (Figures 1, 2).

Effect of Planting Date on Sugars

In 2002, there was no effect of planting date on the sucrose or glucose concentrations at vine-kill or harvest across cultivars (Table 1). However, there were interactions between cultivar and planting date for bud-end sucrose and glucose at vine-kill and stem end sucrose at harvest. Sucrose and glucose concentrations decreased with later planting date in the bud end of Millennium Russet at vine-kill (Table 3). In contrast, bud-end sucrose at harvest increased with later planting date for Umatilla, but this did not result in differences in bud end sugars by harvest.

In 2003, response of sugars to planting date varied across cultivars (Table 4). Sucrose and glucose concentrations increased with later planting date across all cultivars at vine-kill, particularly in the bud-end. The differences in bud-end sucrose and glucose concentrations at vine-kill disappeared by the time of crop harvest except for bud end glucose levels in Defender and Shepody. Stem-end glucose concentrations were unaffected by planting date (Table 4).

Planting date by cultivar interactions on sugars varied between the two years (Tables 3 and 4). In general, planting date had less effect on sugar concentrations at vine-kill in 2002 than 2003. Primary differences in sugar response between years can be seen in the bud end sucrose and glucose concentrations of Millennium Russet at vine-killing. In 2002, Millennium Russet sucrose and glucose concentrations decreased with later planting date. In direct contrast, bud end sucrose and glucose concentrations of Millennium Russet increased with later planting date during 2003.

Effect of Vine-kill Date on Sugars

In 2002, cultivar by vine-kill date interactions affected all sucrose concentrations (Table 1). Bud and stem end sucrose at vine-kill decreased between Aug. 14 and September 18 especially in Umatilla (Table 5). In contrast, bud end sucrose at harvest increased with later vine-kill date except in Umatilla which was unchanged. Vines senesced prior to vine-desiccation for all cultivars in 2002, primarily due to early die syndrome (data not shown). In 2003, cultivar by vine-kill interactions only influenced sucrose concentrations at vine-killing (Table 1). Sucrose levels at vine-kill tended to be lowest at the intermediate vine-kill date (Table 6). Bud end sucrose concentrations were greater than the respective stem-end sucrose concentrations across almost all cultivars and vine-kill dates at time of vine-kill and harvest during both years (Tables 5 and 6).

Cultivar by vine-kill date interactions influenced all glucose concentrations both years except in the bud end at harvest during 2003 (Table 5 and 6). Bud-end glucose decreased with later vine-kill date at the time of vine-kill across all cultivars and years. Stem end glucose increased across all cultivars with later vine-kill date at vine-kill in 2002, but not in 2003. Stem-end glucose concentrations at harvest consistently increased with later vine-kill timing for all cultivars across both years. Stem-end glucose concentrations increased from the time of vine-kill until harvest in all cultivars in 2002. Dramatic increases in stem-end glucose levels for all four cultivars occurred between the third vine-kill date and harvest in 2003 (Table 6). Russet Burbank stem-end glucose levels were consistently high compared to other cultivars in both years. In addition, stem-end glucose was consistently greater than bud-end glucose across cultivars and years (Tables 5 and 6).

Specific Gravity

Overall, specific gravities were lower in 2002 compared to 2003 (Tables 7 and 8). Umatilla had the highest and Shepody the lowest specific gravity in 2002 (Table 7 and 8). Millennium Russet and Defender had the highest specific gravity in 2003 and Shepody had the lowest again (Table 7 and 8). Planting date had a small effect on specific gravity with later planting dates leading to lower specific gravities in 2002 (Table 7). Planting date had no effect on specific gravities in 2003 (Tables 7).

Later vine-kill dates led to higher specific gravities in 2002 (Table 8). Cultivar by vine-kill date interactions in 2002 were due to lack of gravity response in Shepody to vine-kill date. No interaction occurred in 2003 with later vine-kill date increasing specific gravity (Table 8).

Skin-Set

The skin-set rating for Russet Burbank was greater with the earliest and latest planting date, compared to the middle planting date and with the latest vine-kill date in 2003 (Table 9). These data indicate that physical maturity was significantly improved by delayed vine-kill timing.

DISCUSSION

As tubers reach chemical maturity, sucrose levels reach a minimum as starch reserves became maximal (Bussan, 2003). By vine-kill, both glucose and sucrose levels should be at their lowest. Millennium Russet had the lowest average sucrose concentrations in both years of our study, indicating that this cultivar was the most chemically mature at vine-kill of those tested. In contrast, Umatilla and Defender had the highest sucrose concentrations at vine-kill during 2002 and 2003, respectively, implying chemical immaturity compared to the other cultivars. Late maturing cultivars would be expected to reach chemical maturity later than other cultivars. Defender (Novy et al, 2006), Millennium Russet (Groza et al, 2005) and Umatilla (Mosley et al, 2000) were all late-maturing cultivars requiring 120 d growing season for optimal quality and yield. Defender has been reported to lag behind other processing varieties in reaching chemical maturity (Sabba and Bussan, 2005), consistent with the sucrose levels reported here.

Russet Burbank tubers had the highest stem-end glucose concentrations at vine-kill and harvest, and the greatest differences between bud- and stem-end glucose at harvest. These data confirmed reported vulnerability of Russet Burbank to sugar-end syndrome and the tendency for Millennium Russet and Umatilla tubers to have lower glucose compared to Russet Burbank (Groza et al, 2005; Mosley et al, 2000).

Early planting date tended to reduce sucrose and glucose concentrations by vine-kill, especially in 2003. These effects almost entirely disappeared by harvest date, however. The data implies that early planting can reduce sugar concentration at vine kill, but that by harvest the reduction may no longer be significant. Most importantly, in neither year did early planting reduce stem-end glucose levels for any cultivar. Theoretically, an earlier planting date should lead to earlier tuber initiation. Tubers that set earlier may be able to avoid heat stress during early bulking, but this was not observed in these trials. Specific gravity was only slightly affected by planting date in 2002, but not in 2003. The 2002 Umatilla response implies it is possible to improve specific gravity with early planting, at least for some long season cultivars. Nelson and Shaw (1976) reported that Kennebec potatoes planted early had lower concentrations of sucrose at harvest compared to those planted 2.5 to 4 weeks later but only for five of eight harvests. Glucose concentrations were reduced for early planting dates in the same study, but for only two of eight harvests.

As expected, sucrose concentrations decreased between mid August and mid September vine-kill dates in both years, indicating improved chemical maturity during late bulking. As vines senesce and carbohydrate production decreases, sucrose transport into the tuber decreases at the end of the season (Bussan, 2003). While bud-end glucose decreased during this period, stem-end glucose increased during 2002. Increases in stem-end glucose concentration before harvest is not uncommon for russet potatoes (Sabba and Bussan, 2005) and can lead to sugar-end defect that cause fry products to cook dark at one end (Shock, et al, 1993). In 2003, the lowest sucrose concentrations occurred at the intermediate vine-kill date, and in some cases sucrose concentrations increased by the latest vine-kill date. By harvest, stem-end glucose concentrations for the late vine-kill date were much greater than for the earlier vine-kill dates. This raises the possibility that delaying vine-kill until after minimum sucrose levels are achieved in the tuber can contribute to increased stem end glucose by harvest.

Stem-end glucose concentrations at harvest were consistently lower with earlier vine-kill date, which would reduce the tendency of fried products from these potatoes to darken. Vine-killing potatoes that were either less mature or not over-matured appeared to reduce the accumulation of stem-end reducing sugars. Nelson and Shaw (1976) reported that early harvest resulted in greater sucrose concentrations for Kennebec potatoes in two of three experiments. Stem-end glucose concentrations were up to 6.3 times higher than bud-end glucose concentrations in these experiments. A recent report indicated that green vine harvest resulted in the best stem-end fry color for Ranger Russet potatoes grown in Idaho, while vine-kill four weeks prior to harvest resulted in the darkest stem-end fry color (Woodell et al, 2004). This report supports the conclusion that vine-killing can lead to an increased reducing sugar content of russet potato tubers. Our data indicates that vine-killing earlier in the season can reduce this detrimental effect on reducing sugar concentration of tubers destined for processing at harvest, but effects on fry color out of storage need to be confirmed.

Sucrose concentrations were consistently greatest in the bud end, while glucose concentrations were greater in the stem-end. This negative correlation implied more rapid conversion of sucrose to reducing sugars which was likely due to greater invertase activity in the stem end of tubers. Consequently, there were differences in sucrose and glucose concentrations between the two ends of the tuber. While planting date had little effect on specific gravity at harvest, early vine-kill tended to reduce specific gravity, especially in 2002. The fact that specific gravity at harvest increased with later vine-kill timing in conjunction with both glucose and sucrose implies that these sugars did not increase due to a breakdown of starch late in the season.

Both glucose and sucrose levels were up to four fold greater in tubers from the 2002 season compared to the 2003 season across all cultivars. In general, the entire processing crop in WI had lighter fry colors in 2003 compared to 2002 (personal communication, McCain USA). One explanation for this difference may be the heat stress that occurred during the early to mid bulking period during 2002 which also likely led to water-stress. Early season heat and water-stress has been reported as a primary cause of sugar-end in potato (Shock et al, 1993; Eldredge et al, 1996). A single episode of water-stress early in tuber development resulted in sugar-end in Russet Burbank tubers that was not apparent until two weeks or longer after the stress occurred (Eldridge et al, 1996). The lower specific gravity values in 2002 compared to 2003 can also be explained by heat stress in 2002. Heat stress and high soil temperatures have been correlated with a decrease in starch accumulation in tubers and an increase in reducing sugars and poor fry color, particularly at the stem-end (Kincaid et al, 1993; Krauss and Marschner, 1984; Randeni and Caesar 1986; Yamaguchi et al, 1964). Since the dry matter content of potato tuber is mainly dependent on starch (Dean and Thornton, 1992), a reduction in starch would be expected to reduce the specific gravity of the tuber. In addition, early dying appeared to be much more of a factor during 2002 than 2003 which may have also contributed to increased stem-end glucose concentrations. Early dying led to early vine senescence causing increased hill temperature and incidence of sugar end (Rowe and Powelson, 2002). In addition, the early loss of the canopy led to over-maturation of tubers. Over-maturation can lead to increased tuber stem-end glucose concentrations as well (Iritani and Weller, 1980). Soil fumigation can reduce the incidence of early dying, but was not utilized in our study.

The sucrose at vine-kill data indicated it may be possible to reduce sucrose levels by delaying vine-kill, but these results were not carried forward to the first and second harvest dates. The increased sucrose levels that occurred between late vine-kill and late harvest dates in 2003 was unusual and was possibly due to an early freeze before the third harvest. Approximately one third of the tubers were damaged by freezing at the final harvest. Yamaguchi et al (1964) reported that soil temperatures below 16 C can increase tuber reducing sugar concentrations, which would have to come from sucrose breakdown. Similar to 2002, bud-end sucrose concentrations were consistently greater than stem-end sucrose concentrations, while the opposite was true for glucose. Again this is important, because high glucose concentration at one end can lead to sugar-end defect if the tubers cannot be re-conditioned.

Monitoring sucrose and glucose levels (i.e. chemical maturity) has been standard practice for optimizing vine-kill timing and harvest with chipping varieties (Sowokinos and Preston, 1988). Reducing sugar concentration has consistently been the best biochemical indicator of chip color in chipping varieties (Coffin et al, 1987; Herrman et al, 1996; Miller et al, 1975; Rodriguez-Saona and Wrolstad, 1997; Roe et al, 1990). Increasing focus on fry quality of varieties grown for processing suggests that chemical maturity monitoring has the potential to help manage vine-kill and harvest timing for optimal fry color. However, differences in sugar metabolism between the bud and stem-ends in these cultivars pose unique challenges for optimizing chemical maturity. In addition, stem-end glucose concentrations in long processing cultivars tend to increase from vine-kill until harvest unlike with round white chipping cultivars (Sabba and Bussan, 2005). Whether the accumulation of glucose in the bud and stem end of current long processing cultivars can be conditioned as in round white chipping cultivars is yet to be determined.

Despite the importance of physical maturity for the storability of tubers, little research has been reported on the effect of cultural conditions on skin-set. A shear resistance measuring device originally designed by Halderson and Henning (1993) for measuring skin-set has provided researchers with a tool to objectively measure physical maturity of tubers. When attached to a torquometer, this device gave reproducible measurements directly correlated with skin-set (Lulai and Orr, 1993; Pavlista, 2002).

Planting date and vine-kill date affected skin-set in Russet Burbank in our study. While earlier planting dates provided tubers with improved skin-set compared to the middle planting date, there was no difference between late

and early planting dates. The latest vine-kill date, on the other hand, produced the highest skin-set with Russet Burbank tubers. The Russet Burbank tubers with the best skin-set in this study had readings similar to those reported by Halderson and Henning (1993) (214 mN·m and greater) and Pavlista (2002) (310 mN·m and greater) using similar equipment. The fact that skin-set improved for Russet Burbank between the second and third harvest in 2003, while glucose and sucrose increased during the same time period, implies that chemical maturity may occur prior to physical maturity. Waiting for physical maturity in russet potatoes may result in chemical over maturation of the crop and increased fry color. This may explain improved fry color in green dug potatoes (Woodell et al, 2004).

In summary, planting date had a minimal effect on maturation in tubers of most cultivars tested. Later vine-kill timing resulted in increased glucose tuber concentrations, particularly at the stem-end, for all cultivars, but tended to increase specific gravities. At the same time that glucose and sucrose concentrations increased in Russet Burbank tubers with later vine-kill timing, skin-set improved. These results indicate that chemical, physiological and physical maturation does not occur at the same time.

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FIGURE LEGENDS

FIGURE 1. Daily maximum and minimum air temperatures during the 2002 growing season for Hancock, WI. Dotted lines indicate 20 C and 30 C thresholds considered relevant to potato growth.

FIGURE 2. Daily maximum and minimum air temperatures during the 2003 growing season for Hancock, WI. Dotted lines indicate 20 C and 30 C thresholds considered relevant to potato growth.

Figure 1

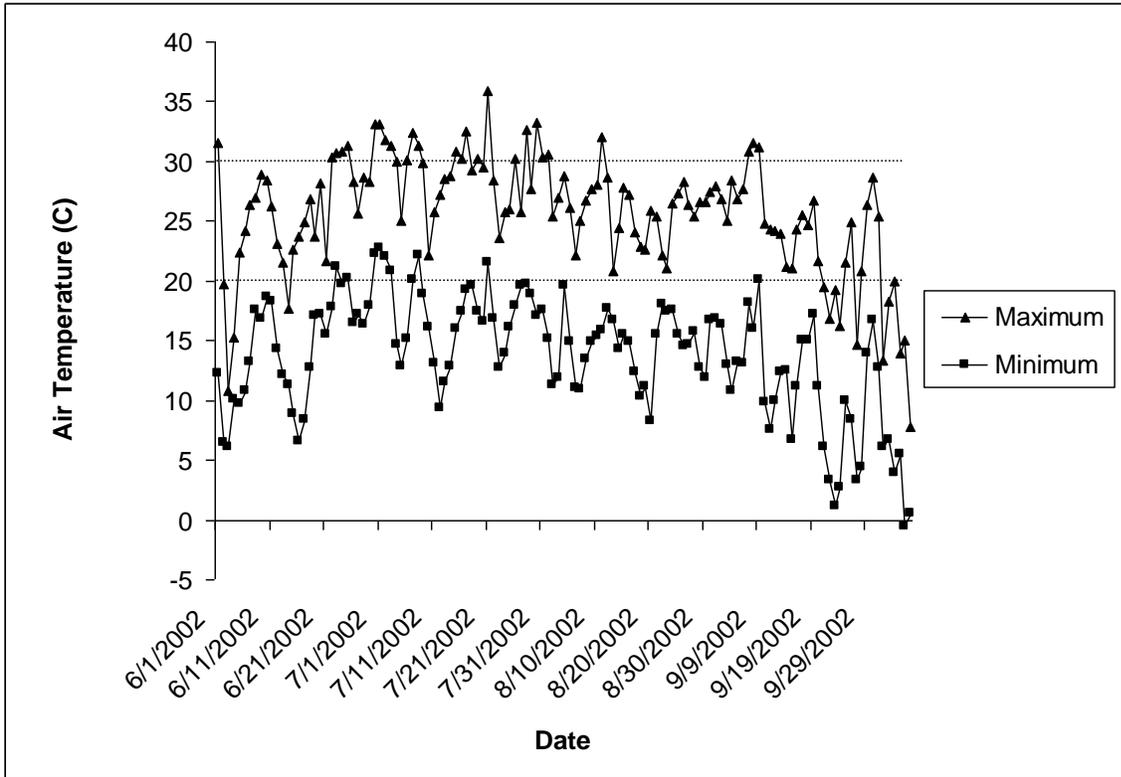


Figure 2

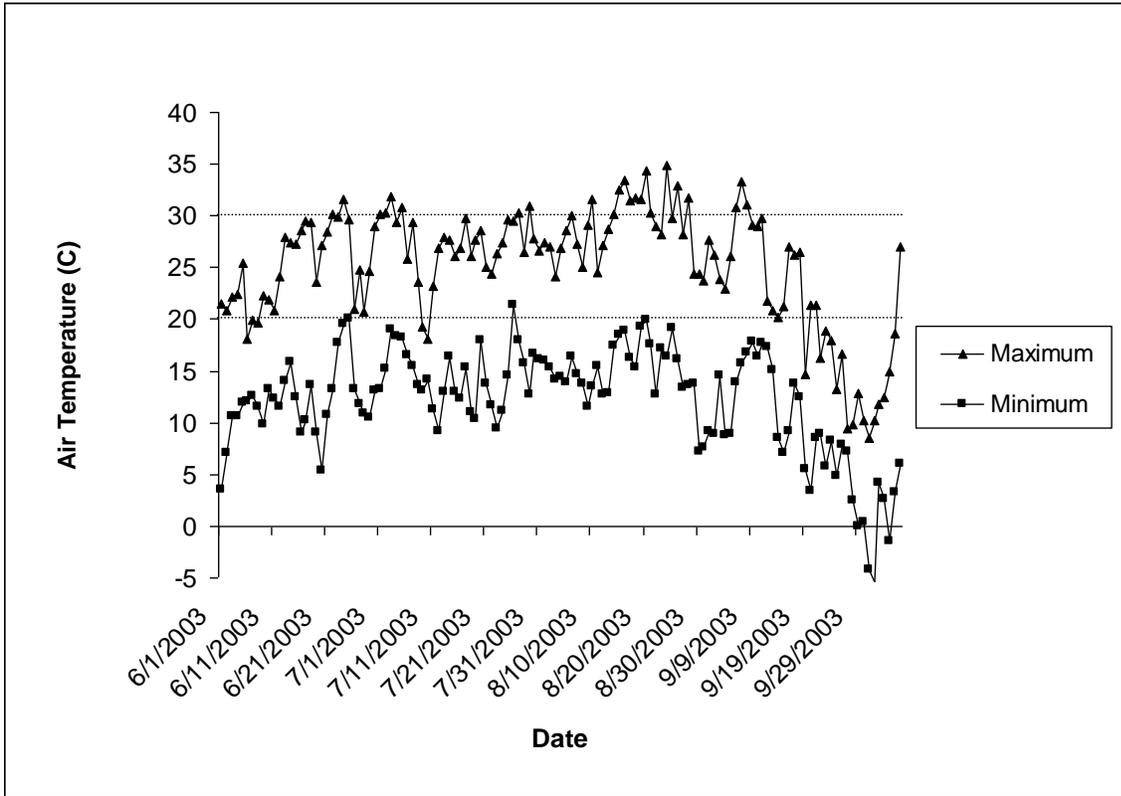


TABLE 1. ANOVA for the effects of cultivar, planting date and vine-kill date on bud-end and stem-end sucrose and glucose and specific gravity during 2002 and 2003. P-values shown for each dependent variable.

*vk = vine-kill date, plant = planting date, cult = cultivar.

Year	Source of Variation*	At Vine-kill				At Harvest				Specific Gravity	
		<u>Sucrose</u>		<u>Glucose</u>		<u>Sucrose</u>		<u>Glucose</u>			
		Bud	Stem	Bud	Stem	Bud	Stem	Bud	Stem		
2002	vk	0.0172	0.0219	0.0016	0.0007	0.0013	0.7558	0.0270	0.0018	0.0040	
	plant	0.9477	0.4161	0.1419	0.7260	0.2658	0.1737	0.7284	0.6684	0.0832	
	cult	<.0001	0.0008	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
	plant*vk	0.3674	0.4122	0.1279	0.4197	0.1803	0.3590	0.4589	0.9060	0.0350	
	cult*vk	0.0088	0.0390	<.0001	<.0001	<.0001	0.0738	0.0033	<.0001	0.0125	
	cult*plant	0.0166	0.3657	0.0541	0.4396	0.4316	0.0184	0.9345	0.6890	0.0924	
	cult*plant*vk	0.4831	0.4723	0.7786	0.4641	0.7556	0.6939	0.0322	0.3112	0.9541	
2003	vk	<.0001	<.0001	<.0001	0.0069	0.2893	0.4556	0.0331	<.0001	0.0423	
	plant	0.0003	0.0049	0.0007	0.3827	0.0545	0.4259	0.8794	0.8556	0.5589	
	cult	<.0001	<.0001	<.0001	0.0002	<.0001	<.0001	0.0079	<.0001	<.0001	
	plant*vk	0.0026	0.8307	0.0011	0.2319	0.9355	0.1989	0.4058	0.9987	0.1815	
	cult*vk	<.0001	<.0001	0.0289	0.1103	0.3622	0.7691	0.8156	<.0001	0.1172	
	cult*plant	<.0001	<.0001	0.0481	0.1028	0.5220	0.3932	0.0978	0.5888	0.2264	
	cult*plant*vk	0.4991	0.8890	0.5795	0.8977	0.8642	0.6753	0.0261	0.1837	0.9910	

TABLE 2. Effect of cultivar on tuber glucose and sucrose concentrations at the time of vine-kill and harvest during 2002 and 2003. All values represent the mean of 33 to 36 replicates, over all planting and vine-kill dates, presented in mg/g fresh weight. Numbers within a column in a given year with the same letter are not significantly different at the 5% level by t-test (LSD).

Cultivar	At Vine-kill				At Harvest			
	<u>Sucrose</u>		<u>Glucose</u>		<u>Sucrose</u>		<u>Glucose</u>	
	Bud	Stem	Bud	Stem	Bud	Stem	Bud	Stem
2002								
Russet Burbank	2.73b	1.79b	0.88a	1.17a	2.94b	1.05c	0.57b	3.41a
Millennium Russet	1.36d	0.71d	0.52bc	0.97a	1.69d	0.41d	1.00a	3.02b
Umatilla	3.44a	3.24a	0.36c	0.44b	2.30c	1.79b	0.67b	2.20c
Shepody	1.86c	1.00c	0.72ab	0.62b	5.01a	2.74a	0.59b	2.93b
2003								
Russet Burbank	1.18b	0.85b	0.15b	0.23ab	1.31b	1.26a	0.23bc	0.96a
Millennium Russet	0.81c	0.46d	0.14b	0.15c	0.91c	0.53c	0.19c	0.63b
Defender	2.37a	1.67a	0.43a	0.28a	1.67a	1.11ab	0.36a	0.71b
Shepody	0.89c	0.62c	0.35a	0.19bc	1.32b	0.90b	0.35ab	0.63b

TABLE 3. Effect of planting date on tuber glucose and sucrose concentrations at the time of vine-kill and harvest for processing cultivars during 2002. All values represent the mean of four replicates presented in mg/g fresh weight.

Cultivar	Planting Date	At Vine-kill				At Harvest			
		<u>Sucrose</u>		<u>Glucose</u>		<u>Sucrose</u>		<u>Glucose</u>	
		Bud	Stem	Bud	Stem	Bud	Stem	Bud	Stem
Russet Burbank	4/16/02	2.67	1.94	0.64	1.33	2.89	1.12	0.59	3.16
	4/26/02	3.49	2.02	1.00	1.39	2.95	0.98	0.56	3.69
	5/6/02	2.72	1.71	0.50	0.85	2.95	1.06	0.55	3.39
Millennium Russet	4/16/02	1.57	0.71	0.77	0.89	2.13	0.50	0.78	3.11
	4/26/02	1.23	0.72	0.45	1.05	1.68	0.32	0.89	3.03
	5/6/02	1.29	0.71	0.35	0.96	1.43	0.42	0.94	3.84
Umatilla	4/16/02	3.22	3.02	0.20	0.29	2.34	2.00	0.73	2.21
	4/26/02	3.53	3.53	0.28	0.41	2.44	1.63	0.60	2.40
	5/6/02	3.64	3.16	0.27	0.39	2.11	1.75	0.69	2.01
Shepody	4/16/02	1.89	0.92	0.74	0.95	5.02	2.79	0.85	2.91
	4/26/02	1.80	1.00	0.66	0.50	4.89	2.60	0.49	3.21
	5/6/02	1.89	1.09	0.77	0.41	5.12	2.82	0.42	2.67
*LSD		0.27	ns	0.29	ns	ns	0.31	ns	ns

*LSD = least significant difference, ns = cultivar and planting date interaction not significant by ANOVA.

TABLE 4. Effect of planting date on tuber glucose and sucrose concentrations at the time of vine-kill and harvest for processing cultivars during 2003. All values represent the mean of four replicates presented in mg/g fresh weight.

Cultivar	Planting Date	At Vine-kill				At Harvest			
		<u>Sucrose</u>		<u>Glucose</u>		<u>Sucrose</u>		<u>Glucose</u>	
		Bud	Stem	Bud	Stem	Bud	Stem	Bud	Stem
Russet Burbank	4/17/03	1.02	0.90	0.12	0.27	1.37	1.47	0.20	0.90
	5/1/03	1.17	0.83	0.17	0.21	1.19	1.09	0.36	0.88
	5/15/03	1.35	0.82	0.18	0.20	1.39	1.21	0.15	1.09
Millennium Russet	4/17/03	0.63	0.47	0.07	0.14	0.87	0.65	0.26	0.60
	5/1/03	0.81	0.46	0.11	0.12	0.83	0.47	0.13	0.61
	5/15/03	0.99	0.45	0.23	0.19	1.03	0.49	0.18	0.67
Defender	4/17/03	1.97	1.50	0.36	0.29	1.56	0.96	0.31	0.76
	5/1/03	2.00	1.39	0.30	0.24	1.67	1.15	0.36	0.69
	5/15/03	3.14	2.125	0.640	0.30	1.77	1.22	0.42	0.70
Shepody	4/17/03	0.77	0.66	0.17	0.11	1.13	0.82	0.32	0.63
	5/1/03	0.95	0.55	0.28	0.21	1.38	0.77	0.28	0.67
	5/15/03	0.94	0.64	0.60	0.24	1.45	1.11	0.46	0.59
*LSD		0.16	0.10	0.09	0.05	ns	ns	0.10	ns

*LSD = least significant difference, ns = cultivar and planting date interaction not significant by ANOVA.

TABLE 5. Effect of vine-kill date on tuber glucose and sucrose concentrations at the time of vine-kill and harvest for processing cultivars during 2002. All values represent the mean of four replicates presented in mg/g fresh weight.

Cultivar	Vine-kill Date	At Vine-kill				At Harvest			
		<u>Sucrose</u>		<u>Glucose</u>		<u>Sucrose</u>		<u>Glucose</u>	
		Bud	Stem	Bud	Stem	Bud	Stem	Bud	Stem
Russet Burbank	8/14/02	4.01	2.38	0.90	0.36	2.62	1.15	0.49	3.00
	8/30/02	2.45	1.66	0.81	1.41	3.07	0.98	0.56	3.42
	9/18/02	2.27	1.60	0.36	1.75	3.13	1.06	0.66	3.81
Millennium Russet	8/14/02	1.84	1.07	0.80	0.39	1.26	0.17	0.75	2.52
	8/30/02	1.16	0.63	0.06	1.08	1.85	0.57	0.90	3.06
	9/18/02	1.09	0.44	0.15	1.44	2.09	0.48	0.96	3.37
Umatilla	8/14/02	5.32	4.76	0.32	0.15	2.20	1.95	0.65	1.86
	8/30/02	2.66	2.51	0.27	0.41	2.24	1.74	0.74	2.24
	9/18/02	2.16	2.30	0.14	0.56	2.45	1.69	0.62	2.51
Shepody	8/14/02	2.03	1.21	1.32	0.27	3.25	2.02	0.73	1.56
	8/30/02	1.80	0.87	0.52	0.89	5.40	2.68	0.47	3.04
	9/18/02	1.75	0.93	0.33	0.69	6.37	3.52	0.57	4.19
*LSD		0.27	0.18	0.29	0.20	0.36	0.31	0.14	0.29

*LSD = least significant difference, ns = cultivar and vine-kill date interaction not significant by ANOVA.

TABLE 6. Effect of vine-kill date on tuber glucose and sucrose concentrations at the time of vine-kill and harvest for processing cultivars during 2003. All values represent the mean of four replicates presented in mg/g fresh weight.

Cultivar	Vine-kill Date	At Vine-kill				At Harvest			
		Sucrose		Glucose		Sucrose		Glucose	
		Bud	Stem	Bud	Stem	Bud	Stem	Bud	Stem
Russet Burbank	8/19/03	1.60	1.12	0.24	0.16	1.25	1.13	0.15	0.38
	9/3/03	0.94	0.59	0.10	0.17	1.14	1.02	0.08	0.44
	9/15/03	1.00	0.85	0.12	0.35	1.56	1.62	0.48	2.06
Millennium Russet	8/19/03	1.16	0.64	0.26	0.26	0.88	0.54	0.10	0.30
	9/3/03	0.57	0.35	0.08	0.08	0.78	0.43	0.08	0.39
	9/15/03	0.70	0.39	0.07	0.11	1.08	0.64	0.39	1.19
Defender	8/19/03	3.40	2.51	0.77	0.33	1.64	1.12	0.34	0.40
	9/3/03	2.17	1.38	0.29	0.18	1.32	1.00	0.26	0.31
	9/15/03	1.54	1.12	0.24	0.32	2.04	1.20	0.49	1.43
Shepody	8/19/03	0.99	0.83	0.61	0.17	1.40	0.82	0.34	0.31
	9/3/03	0.82	0.50	0.22	0.12	1.08	0.70	0.21	0.27
	9/15/03	0.85	0.51	0.23	0.28	1.47	1.17	0.53	1.31
*LSD		0.16	0.10	0.09	ns	ns	ns	ns	0.11

*LSD = least significant difference, ns = cultivar and vine-kill date interaction not significant by ANOVA.

TABLE 7. Effect of planting date on tuber specific gravity for processing cultivars during 2002 and 2003. All values represent the mean of four replicates.

Cultivar	Planting date		
	4/16/02	4/26/02	5/6/02
Russet Burbank	1.0778	1.0781	1.0778
Millennium Russet	1.0779	1.0773	1.0768
Umatilla	1.0811	1.0791	1.0763
Shepody	1.0707	1.0705	1.0695
*LSD	0.011		

Cultivar	Planting date		
	4/17/03	5/1/03	5/15/03
Russet Burbank	1.0800	1.0793	1.0788
Millennium Russet	1.0835	1.0838	1.0822
Defender	1.0820	1.0826	1.0832
Shepody	1.0773	1.0749	1.0753
*LSD	ns		

*LSD = least significant difference based on cultivar and planting date interaction,
 ns = cultivar and planting date interaction not significant by ANOVA.

TABLE 8. Effect of vine-kill date on tuber specific gravity for four processing cultivars during 2002 and 2003. All values represent the mean of four replicates.

Cultivar	Vine-kill date		
	8/16/02	8/30/02	9/18/02
Russet Burbank	1.0771	1.0778	1.0788
Millennium Russet	1.0743	1.0788	1.0790
Umatilla	1.0783	1.0777	1.0806
Shepody	1.0695	1.0709	1.0703
*LSD	0.011		

Cultivar	Vine-kill date		
	8/19/03	9/3/03	9/15/03
Russet Burbank	1.0787	1.0800	1.0795
Millennium Russet	1.0816	1.0843	1.0837
Defender	1.0798	1.0837	1.0844
Shepody	1.0752	1.0767	1.0756
*LSD	ns		

*LSD = least significant difference based on cultivar and vine-kill date interaction,
 ns = cultivar and planting date interaction not significant by ANOVA.

TABLE 9. Effect of planting and vine-kill date on skin-set of Russet Burbank tubers for 2003. All values are presented as the torque required to excoriate the periderm. Numbers within a column with the same letter are not significantly different at the 5% level by Tukey's Studentized Range test.

Planting Date	Skin-Set (mN'm)
4/17/03	298a
5/1/03	278b
5/15/03	289ab

Vine-Kill Date	Skin-Set (mN'm)
8/19/03	286a
9/3/03	272a
9/15/03	306b