Department of Agriculture, Trade and Consumer Protection
Division of Agricultural Development
Agricultural Development & Diversification Program (ADD)
Grant Project Final Report

Contract Number: 21028

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

Amount of Funding Awarded: $25,000

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1) What was the original intent of the grant?
   - What did you want to accomplish with the grant?

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.
Specific objectives:
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

- How was it expected to benefit Wisconsin Agriculture?

Fry color has been directly correlated to the reducing sugar content of tuber tissue. Reducing sugars react with free amino acids during frying via the Maillard reaction resulting in brown to black discoloration of the tuber tissue, which is considered undesirable by consumers. Management practices during potato production and storage can have direct impacts on the reducing sugar content of potato tubers. Development and implementation of production and storage management practices that reduces reducing sugar content and improves fry color will improve the value of processing potatoes in Wisconsin increasing contract acres and prices for growers, and end product value to processors.

- What makes this project work important or significant?

Wisconsin farmers produced 65,000 acres of potato with an annual farm gate value of over $200 million. Wisconsin also has a strong potato processing industry that includes value added products such as chips, fries, frozen processed potatoes, fresh pack and seed potatoes that increases the value of the WI potato industry to almost $1 billion. Numerous jobs exist within the potato processing and value added industries in WI. Approximately 35% of the WI potato crop is processed into frozen products such as French fries. The greatest value in processed potatoes is by production for food service industries (fast food restaurants). Recent declines in demand for potato and increased competition (Canada) from foreign suppliers has reduced the value of potatoes and led to a 25% decline in potato acreage in Wisconsin since 2003. WI potato growers must grower a better quality crop in order for the processed

industry to remain competitive in shrinking potato markets. New incentives have been introduced by potato processors for improve fry color in processed potatoes. Processed potato with better fry color will generate greater demand and price for WI produced potato.

2) What steps did you take to reach your goal?

Objectives 1 and 2 were addressed with several research trials conducted at the University of Wisconsin-Madison, Hancock Agricultural Research Station. Experiments were conducted to manipulate maturity of potatoes and monitor corresponding sugar levels in the crop before harvest, at harvest, and out of storage. Trials included experiments that manipulated maturity by adjusting planting and vine kill timing (Bussan), fertilizer rate (Bussan), harvest date with or without vine desiccant (Bethke), and vine kill product and time of application (Colquhoun). Most experiments evaluated multiple varieties.

Objective 3 was also addressed with multiple experiments. Small scale irrigation trials were conducted on the Hancock Ag Research Station evaluating the influence of irrigation frequency, hill shape, and nitrogen fertility program on the potato reducing sugar content and fry quality. Limitations in flexibility of irrigation equipment only allowed 2 allowable depletions levels to be established at 25 and 50%. Experiments were conducted in the Biotron on the UW-Madison campus to quantify the interaction of soil temperature and timing of moisture deficit on sugar levels in Russet Burbank potatoes. Field scale trials were also conducted with growers who adjusted irrigation frequency. Crop quality and soil moisture content were monitored in field scale trials. Finally, we are evaluating commercial scale storage bins (2,000 cwt) of potatoes in collaboration with McCain for long term processing potential.

- What worked?

Two major findings relate to chemical maturity of Russet potatoes and variety. Chemical maturity of Russet potatoes appears to occur when sucrose levels are minimized, but prior to increases in stem end glucose levels. This appears to occur at the same time Russet Burbank stops bulking. Delaying harvest beyond chemical maturity increases reducing sugar content in storage and leads to poorer fry color.

Several varieties appear to have improved processing potential compared to Russet Burbank. Freedom Russet and Bannock Russet both have good to excellent fry color out of the field and out of storage. Current evaluations of commercial scale storage of both Freedom and Bannock Russet are encouraging after 2 months (Figure 1). Little stem end darkening was visible on any potato as of early November and fry color was good to excellent. Fry samples last week indicate that stem end darkening has occurred on some Russet Burbank, but Freedom and Bannock still have good to excellent color.

Prelimary results from the Biotron suggest increased irrigation frequency improved fry color of Russet Burbank. Grower results from field scale experiments have also suggested increased irrigation frequency improved fry color and reduced the incidence of sugar end. Field trials at Hancock have been less conclusive, but will be continued in 2008 to overcome some troubles with disease management.

- What challenges did you face?

Early dying continues to be a confounding factor in research trials at the Hancock Ag Research Station. Results of multiple small plot experiments (especially the irrigation trials) were confounded by early dying of potatoes.

- What would you do differently?

We are going to complete the irrigation study for a third year under separate funding. This is necessary to test hypothesis related to irrigation frequency and confirm observations from greenhouse trials that indicate higher irrigation frequency is necessary to lower sugar concentrations and improve fry color. To decrease the effects of early dying, fumigation will be completed when soils are at field capacity and fields will be irrigated to ensure proper incorporation of fumigant.

Figure 1. Freedom Russet, Bannock Russet, and Russet Burbank fries out of storage after being cooled to 47 F on 11/5/07.

3) What were you able to accomplish?

- What are the results from this project?
- Include any analysis of data collected or materials developed through project work.

Not all research is completed yet as storage samples are still being processed for 3 of the four experiments completed in relation to objectives 1 and 2. In addition, irrigation trials designed to address objective 3 will be repeated in 2008 under separate funding. Results to date can be viewed in the attached files:

Fry color recs.pdf

Vine kill paper 1-2-07.doc

Additional publications will be made available to the ADD program as they are completed over the next 12 to 18 months.

We also received over $80,000 in additional funds from the USDA Potato Research and Marketing competitive grant program to conduct research related to this project.

4) What conclusions can you make based on project work the analysis of collected data?

Current recommendations related to management of chemical maturity can be seen in the attached document (final editing for publication by extension):

Maturation of potatoes 10-31-07.doc

Current conclusions:
a-early dying leads to over maturation and poor fry color
b-over maturation due to other factors also causes poor fry color
c-harvesting immature potatoes can also reduce fry color, but less so than over maturation.

Other conclusions:
Russet Burbank almost always has elevated glucose in the stem compared to the bud end thus almost always has darker fry color on the stem end. Dramatic changes in the management system will be necessary to meet future color standards including:
a-harvest of green (non-desiccated) Russet Burbank potatoes
b-production of alternative varieties such as Bannock Russet, Freedom Russet, Umatilla Russet, or Premier Russet

Other conclusions are based on preliminary research results and grower response to recommendations regarding more frequent irrigation, planting in flat hills, and other proposed management changes.

5) What do you plan to do in the future as a result of this project?

I am working with several colleagues to update irrigation management bulletin for irrigated vegetables and this will include information relative to irrigation frequency in potatoes for minimizing sugar end and improving fry color. This will be done in 2009 once irrigation trials can be completed again and additional information is available regarding use of soil moisture monitoring equipment in irrigated potato production.

Hypotheses to be further tested and confirmed in on farm monitoring include the identification of chemical maturity defined earlier and relation to storage quality and tuber bulking

We will continue to work in collaboration with McCain and Kettle foods to address issues related to management of Russet Burbank as well as potential of new varieties such as Bannock Russet, Freedom Russet and others to meet processing needs of WI.

We are also studying the source of stem end darkening in chipping potatoes and methods of preventing its development. This is a new project and does not appear to be physiologically related to sugar end development in russet potatoes. However, this research allowed us to be competitive for these funds. Recently approved grant at $134,000 was approved by the US Potato Board.

6) What information or additional resources are needed to commercially develop this enterprise?

Completion of additional on farm demonstration trials, finalization of tuber maturation and irrigation bulletins, and continued educational programs with the WI potato industry and McCain is planned. In addition, two management bulletins for optimization of Freedom Russet and Bannock Russet production systems are in preparation.

7) How should the agricultural industry use the results from your grant project?

WI processed potato growers who want to improve fry color need to: 1) prevent drought events during tuber initiation and early bulking (corresponds to May 25 through July 31 the last 2 years), 2) prevent early dying and maintain healthy crop growth through August 31, 3) Harvest Russet Burbank within 21 d of vine killing.

Importance of Tuber Maturation for Improving Potato Storability

Optimizing skin-set, sugars, and solids

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Wisconsin farmers produce over 30 million cwt (hundred weight) of potatoes annually for fresh market, processing, chips, and seed. The farm gate value of the Wisconsin potato crop exceeds $200 million annually. The impact of potato on the state economy increases when considering the value added by processing potatoes.

To ensure a steady supply of raw product year-round, up to 80% of the potato crop is stored in climate-controlled warehouses. Typically, about 10% of the crop is lost to breakdown during storage. More than 20% of the stored crop was lost during 2000 and 2001, costing Wisconsin potato farmers an estimated $32 million.

Maximizing the value of the stored potato crop in Wisconsin requires careful crop management going into storage. Good storability equates to potatoes going into and coming out of storage with good quality. Storage losses are primarily due to shrinkage and spoilage. Shrinkage is the loss of moisture and carbon from the tubers through 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 leading to catastrophic losses.

Potatoes may also be rejected by end users due to deterioration of quality during storage. Quality factors of the stored potato crop differ based on end use. Fresh market potatoes can be rejected for bruises and surface blemishes. Processing and chip potato quality factors include solid content, bruises, and fry or chip color. Seed potatoes quality factors include sprouting, presence of disease on tuber surfaces, and bruises.

Harvesting tubers at peak maturity ensures good storability. Maturity refers to four distinct processes that occur as the crop approaches harvest (table 1). Vine maturation or senescence triggers tuber maturation. The tubers must mature **chemically** for optimal chip and fry color, **physiologically** for maximum yields and quality, and **physically** to minimize skinning, shrinkage, and disease development during storage. Each process is described below along with recommended management practices that increase the likelihood of producing potatoes 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	Promotes tuber maturity and storability	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. Kill vines 2 to 3 weeks prior to harvest.	Monitor sucrose content before and after vine kill. Harvest tubers when sucrose is at a minimum (<1.0 mg/g fresh weight).	Monitor specific gravity before harvest. Harvest when specific gravity is maximal.	Kill vines 2-3 weeks before harvest. Confirm sufficient skin set prior to harvest

Potato Vine Maturation

Vine maturation occurs over the final 2 to 3 weeks of potato plant growth. Ideally, this corresponds with the final 2 to 3 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 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 Wisconsin 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 began senescing 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). Delayed maturation is believed to have contributed to increased storage losses during 2000 and 2001.

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.

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, 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: <u>Types of sugars</u>

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, high concentrations of sucrose can breakdown and lead to 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 fresh weight 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 more susceptible to cold sweetening compared to mature tubers. The set point, or minimum storage temperature, will have to be higher for chemically immature potatoes. 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.

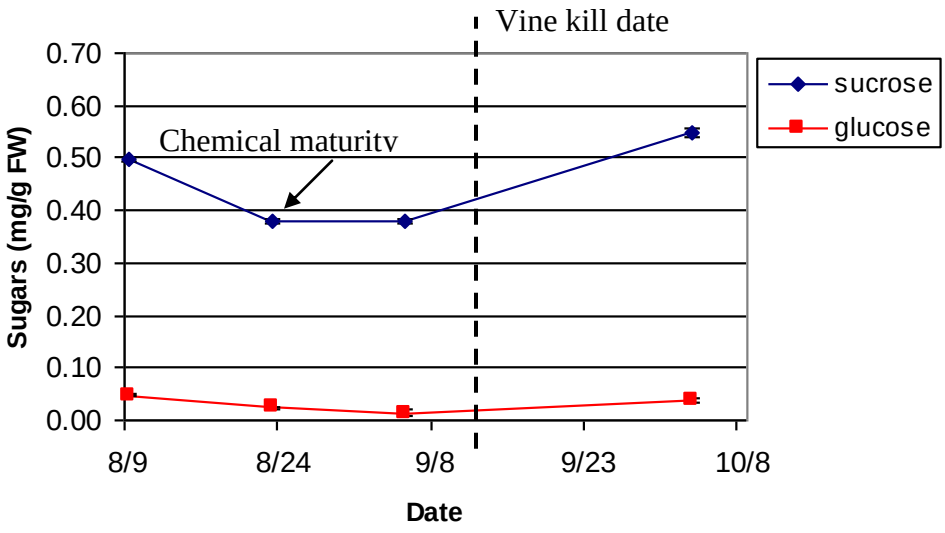
Chemical Maturity Monitoring. Monitoring chemical maturity of chipping potatoes has been common practice for several decades. Chemical maturity is determined by quantifying the sucrose concentration of the potato tubers. Russet potatoes for processing have rarely been monitored for chemical maturity. Chip 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. Collect a single mid-sized tuber (6 to 10 oz in size) 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 commonly used method 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. (www.techmark-inc.com/ or 517.322.0250) in Michigan is the closest consulting firm to Wisconsin that will process potato tuber samples for sugar concentrations.

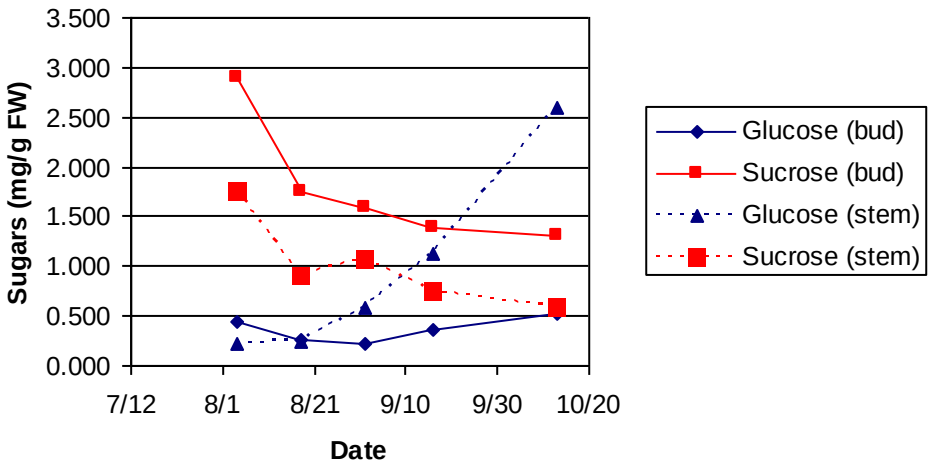
Chemical maturation of chipping potatoes should be monitored to minimize tuber sugar concentrations prior to vine desiccation and harvest. Most chip potatoes are chemically mature between mid-July and mid-August. Chemical maturity of Dakota Crisp occurred before the end of August in 2006 at Hancock (Figure 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, high concentrations of 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 fresh weight 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 fresh weight or lower. Variety specific information can be obtained through state extension specialists.

Insert: New potato varieties such as Premier or others 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 days of crop emergence or at least 30 days prior to vine desiccation. No yield or quality benefits have been observed when nitrogen has been applied later than 45 days 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. Irrigation should be continued to maintain soil moisture levels above the critical level through harvest, but over-irrigation should be avoided after vine killing.

Preventing over-maturation can be just as important as managing for chemical maturity. Over maturation also leads to elevated sugar concentrations. Premature vine death due to inadequate fertilization, drought stress, early dying, or other causes can result in over maturation of potato tubers and increased tuber sucrose levels. Long delays in harvest following 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

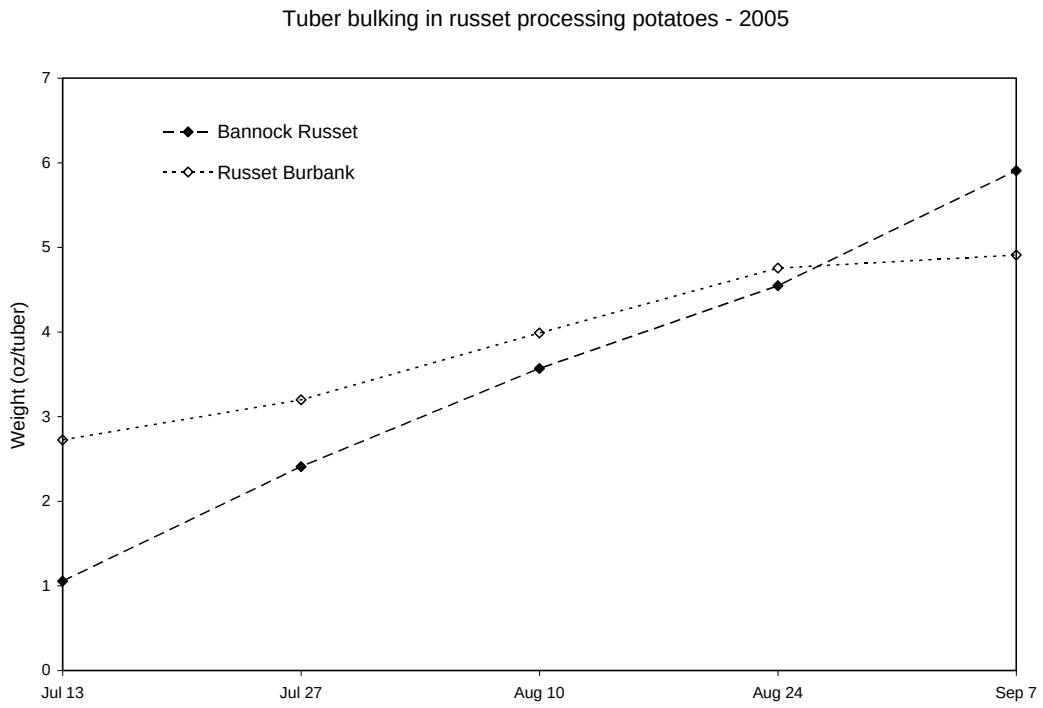
Process. Physiological maturity refers to the state of the dry matter content of the potato tubers. Starch is the primary storage carbohydrate in potato tubers. Potatoes with high starch and low sucrose content generally have better processing characteristics and better attributes for fresh market potatoes. Starch and dry matter content continue to increase until potato tubers mature. Correspondingly the specific gravity, or solid content, 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 reduce 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 measurement 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 tubers

reached 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.



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).

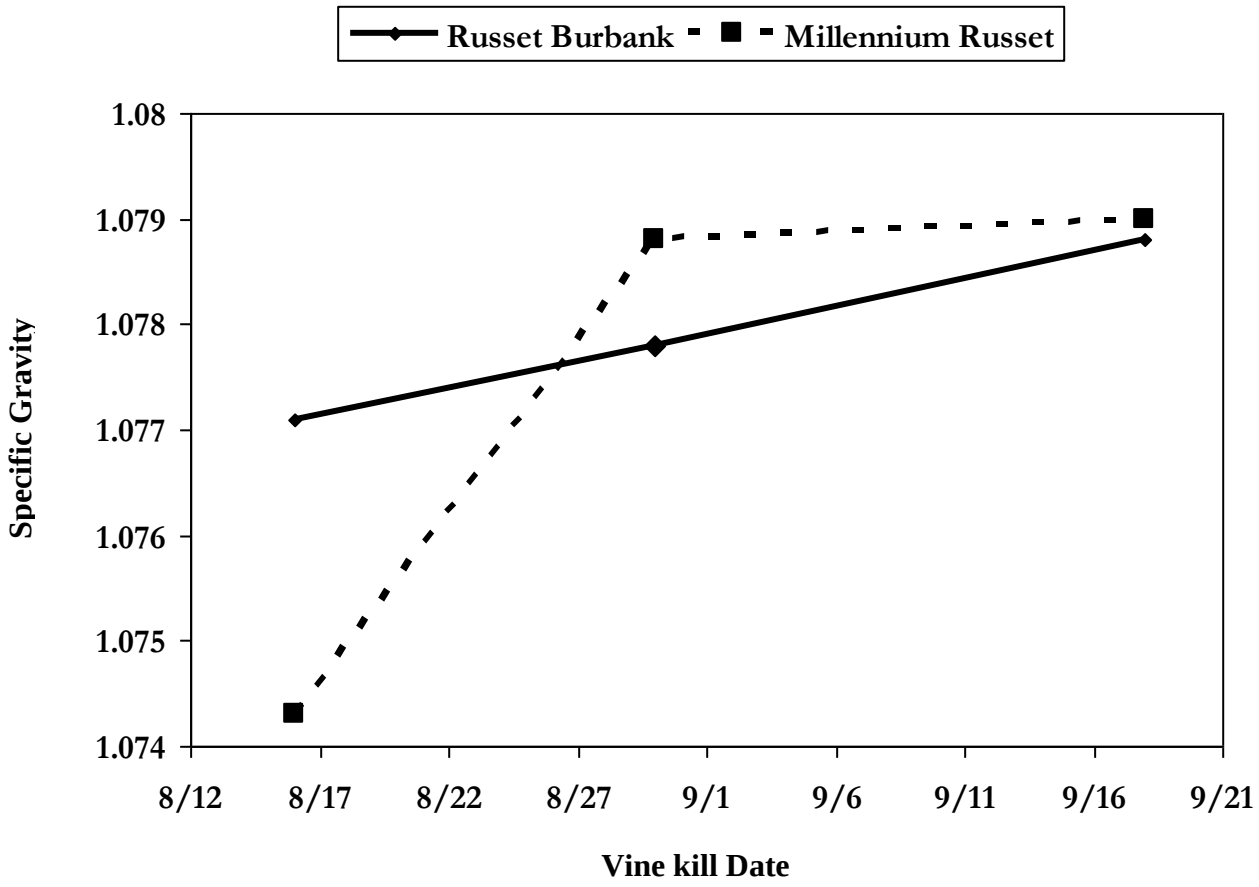
Several methods are available for determining tuber specific gravity. Hydrometers are available from multiple sources. Suspend predetermined weight of potato tubers in a basket and suspend from the hydrometer in water. The specific gravity is determined by estimating the level of the water on the scale.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

Specific gravity = weight in air / (weight in air – 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

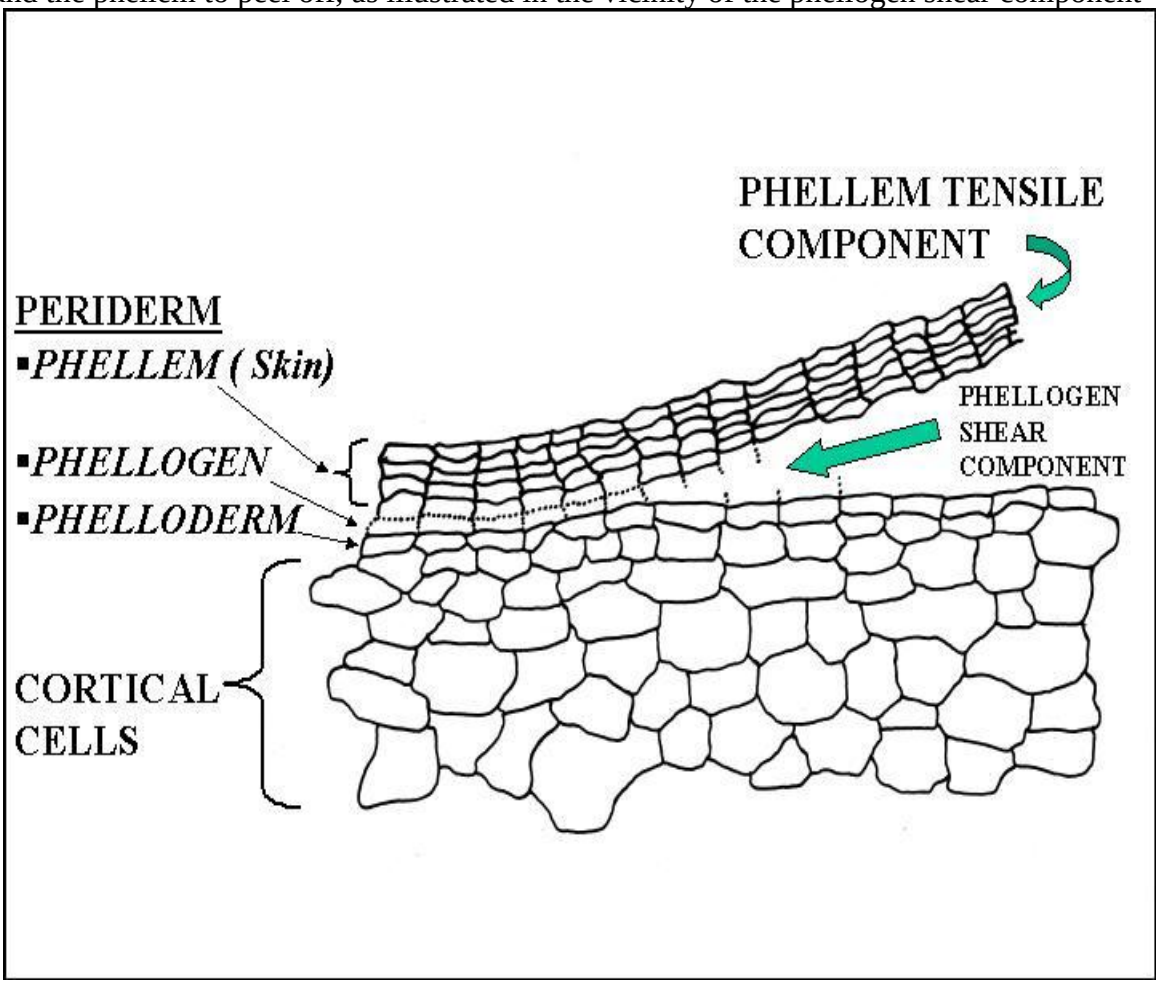
Process. Physical maturity relates to skin set on potato tubers. Skin-set refers to the resistance to skinning injury. Potato tubers expand rapidly during late tuber bulking. The skin which is part of the periderm, must be capable of expanding with the growing tuber. As the crop starts to mature, potato tubers stop expanding and the skin starts to set. Skin set is a key process of potato maturation and protects 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, well before skin set.

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

Vine kill date

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 during tuber bulking. The skin of a growing tuber is easily damaged or removed by 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. (See sidebar for more details about suberin)

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 take longer 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 turgidity within cells. Decreased turgidity 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 russeting. 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: About suberin

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.

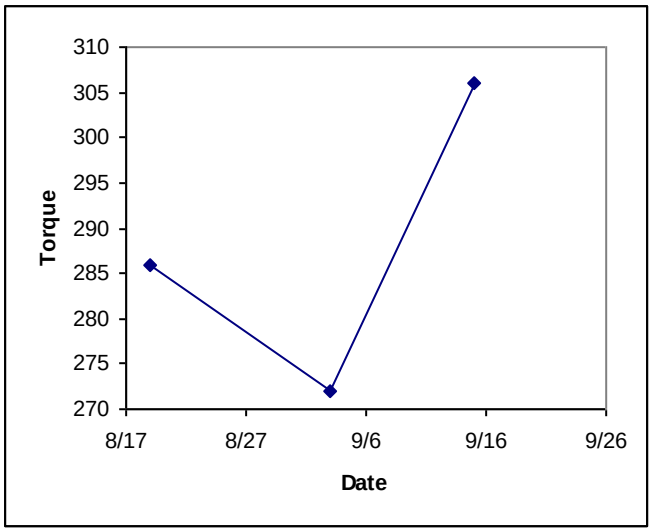
Monitoring physical maturity. Monitoring physical maturity requires measurement of force required to remove the potato periderm. Modified torqueometers have been used to quantify skin set in research trials. Physically mature tubers require more torque to remove the periderm than immature tubers. However,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

Skin set can simply be assessed by rubbing your thumb against the skin to try and remove the periderm. The periderm can be easily sloughed on immature tubers, whereas mature tubers require greater force to remove the skin. Air dry tubers for several hours 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 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 and varieties within types differ 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. 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 CO_2 accumulation in the storage atmosphere. The duration of purging will vary depending on storage volume, air speed and outside versus inside air temperature. Elevated CO_2 delays development of the closing layer and promotes development of anaerobic bacteria that can infect potato tubers and cause decay.

Overall Crop Management

The goal is to manage potatoes so chemical, physiological, and physical maturity occurs simultaneously. In reality, the timing of different phases of maturation are not always coordinated because of slight differences in the processes influencing their development. However, the following 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. Keeping the vines green and actively growing up until the time of vine desiccation and harvest will delay tuber maturation and result in harvest of immature potato tubers. Conversely, if the 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 promotes maximum translocation of carbohydrates from the crop canopy to the tubers resulting in maximum specific gravity and yield, and initiation of skin set. In addition, natural plant senescence should reduce the flow of sucrose to the tubers allowing conversion to starch and minimizing tuber sugar concentrations.

Managing plant maturation

Crop fertility, specifically nitrogen, has large effects on canopy growth and development. Nitrogen fertilizer rates must be optimized to maximize yield, but excess nitrogen applications avoided to promote 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 days after crop emergence or 40 to 45 days 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 and at amounts sufficient to re-wet the potato rooting zone. Irrigation amounts need to be adjusted as vines senesce to reflect the diminishing evapotranspiration by the declining canopy.

Vine desiccation is the final step for promoting maturation of potato tubers. Vine desiccants should be applied at least 21 days prior to intended harvest date to promote tuber skin-set and 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.

Vine desiccants vary in their relative activity. Some desiccants kill vines within 12 to 24 hours while others require several days. Follow label directions for effective potato vine desiccation.

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

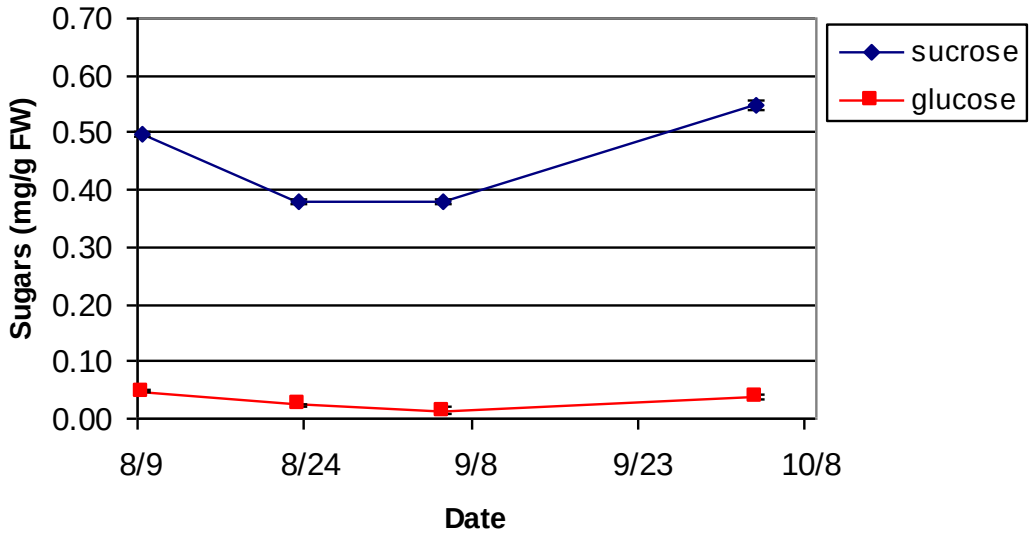


Figure 2. Sucrose and glucose concentration in bud and stem end of Russet Burbank tubers from August through September.

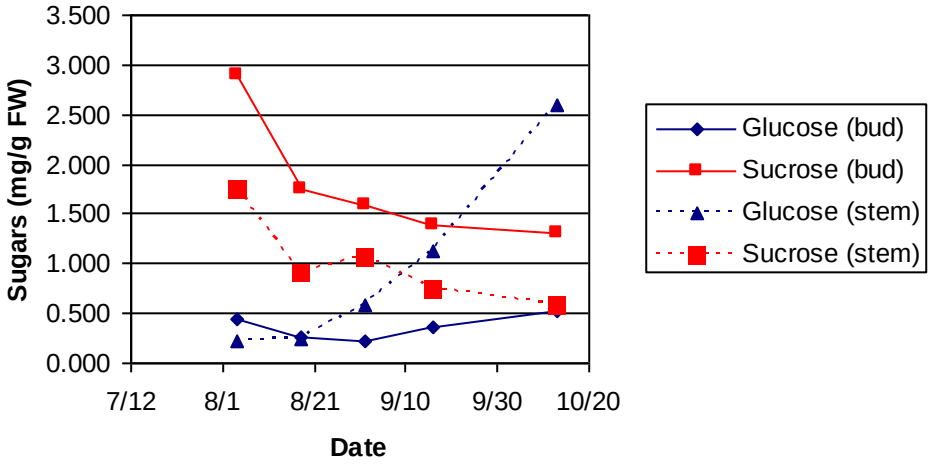


Figure 3. Average tuber size of Russet Burbank and Bannock Russet from early July through mid September during 2005.

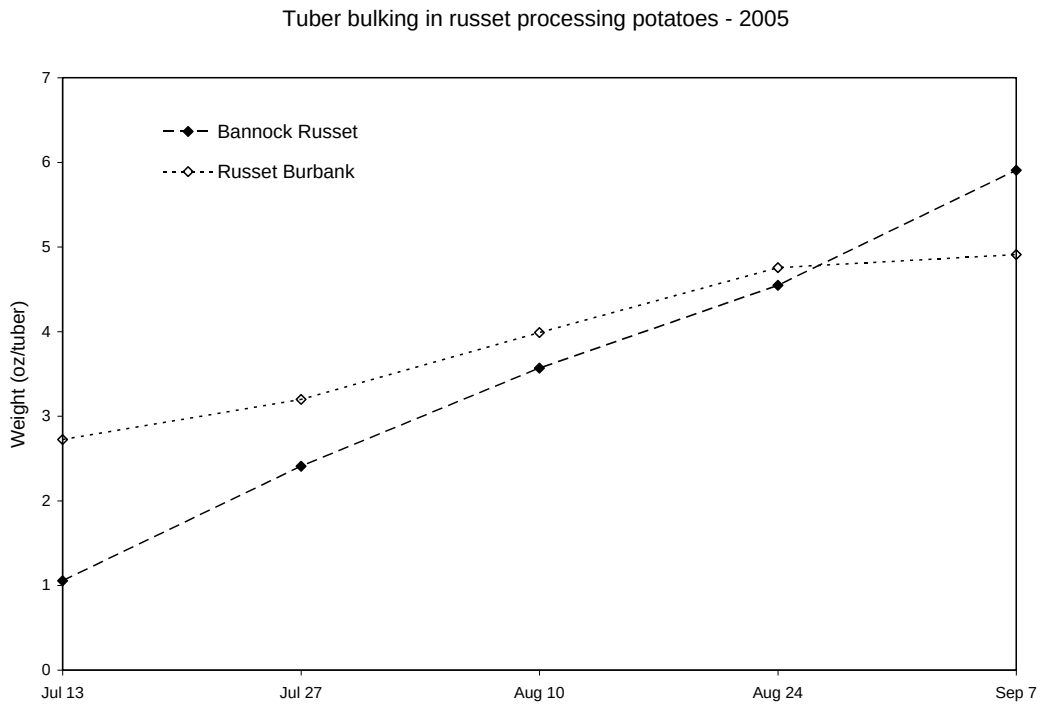


Figure 4. Effect of vine-kill timing on specific gravity of Russet Burbank and Millennium Russet Potato.

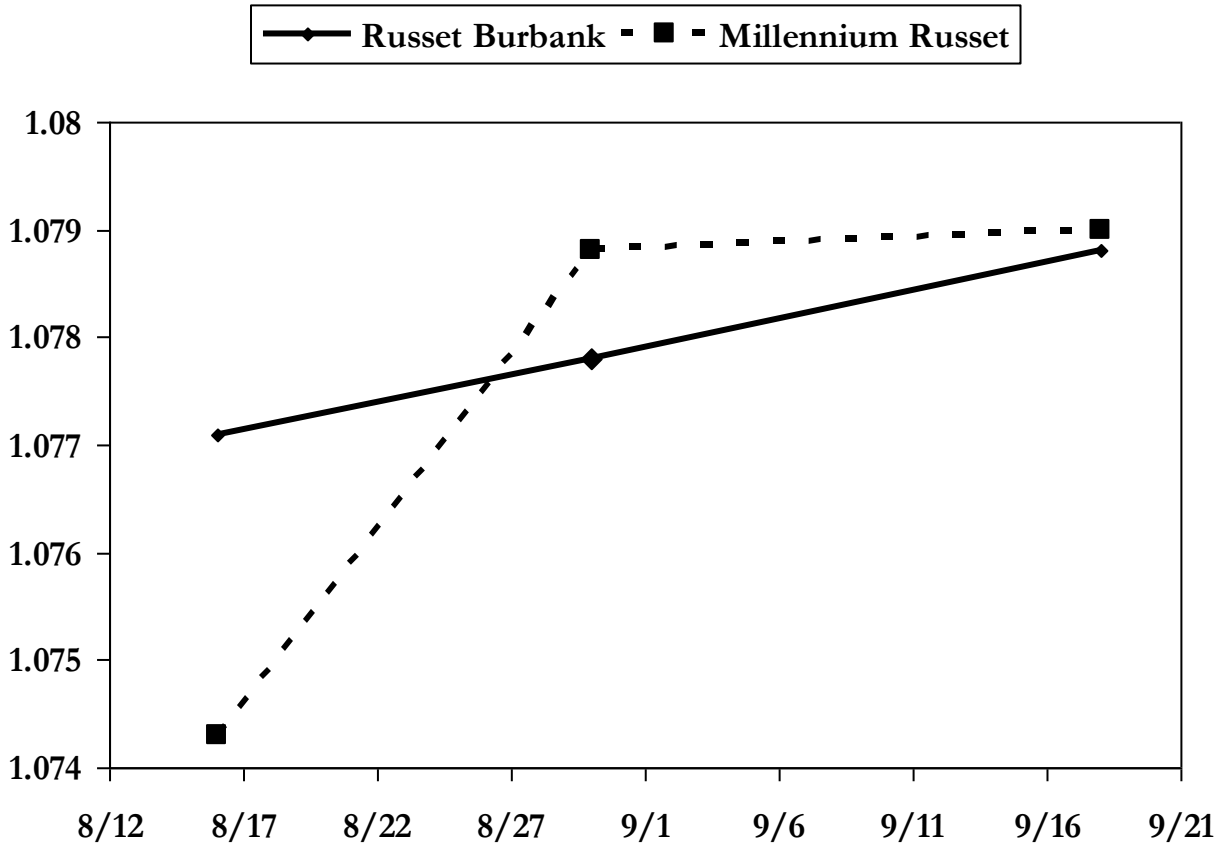


Figure 5. A diagram of the potato periderm showing the phellem, phellogen, and phelloderm. Skinning occurs when physical forces cause phellogen cells to break and the phellem to peel off, as illustrated in the vicinity of the arrow.

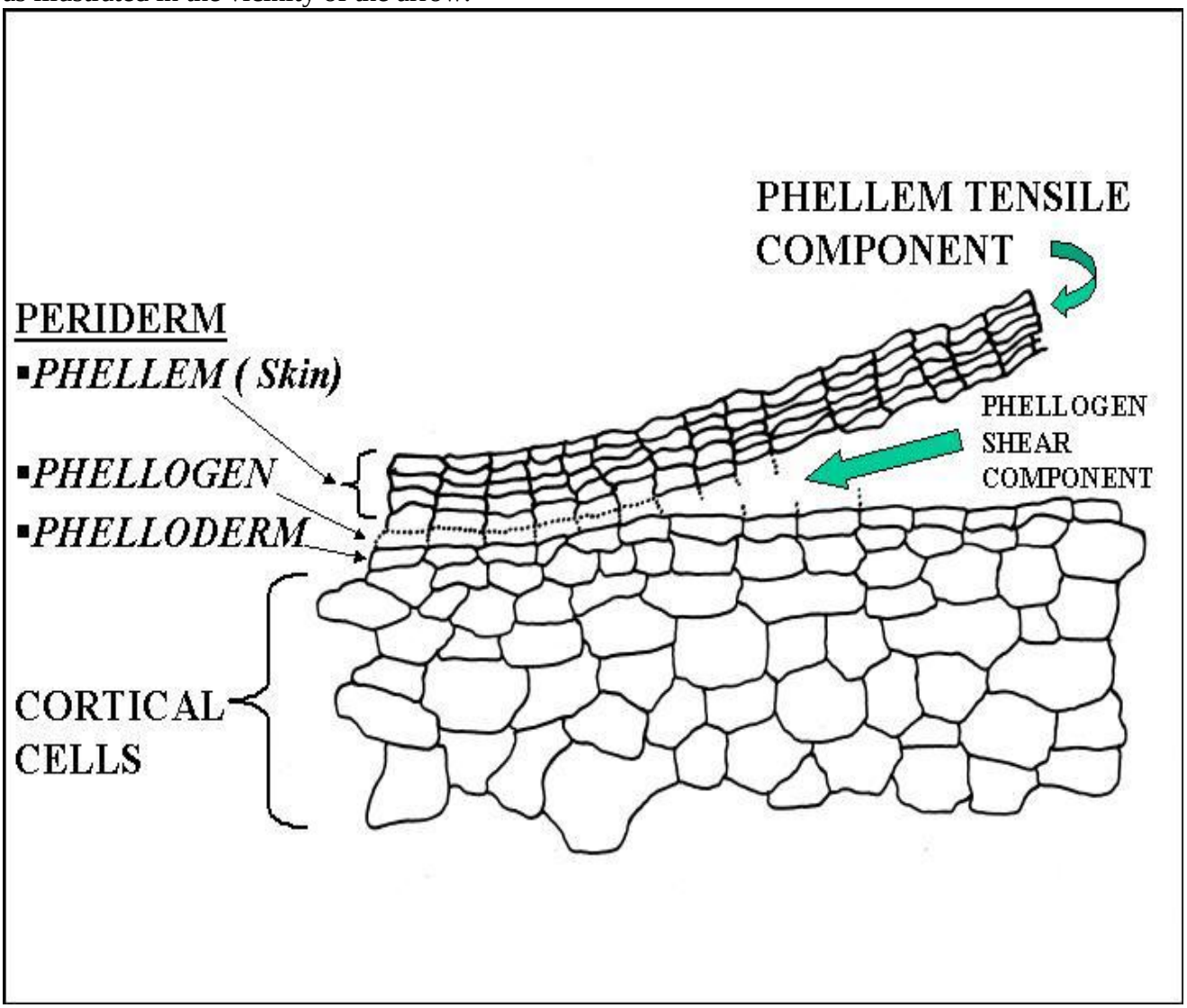
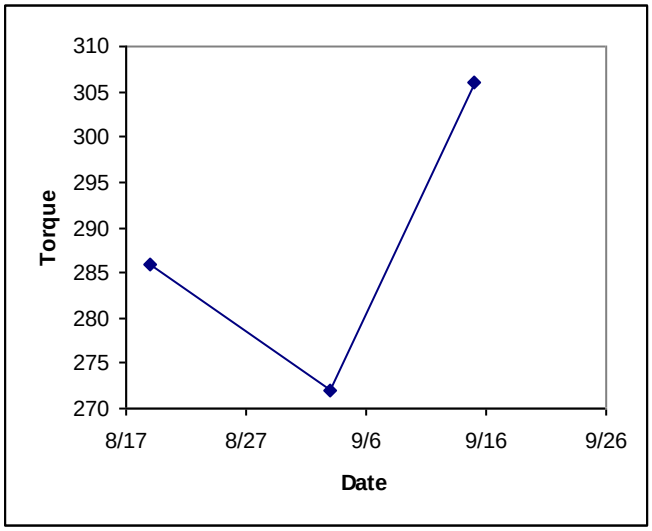


Diagram republished with permission from E.C. Lulai (2002) Am. J. Pot. Res. 79: 241-248

Figure 6. Skinnning 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] pyrazediium 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 affects 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 affects 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 at 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.

ACKNOWLEDGEMENTS

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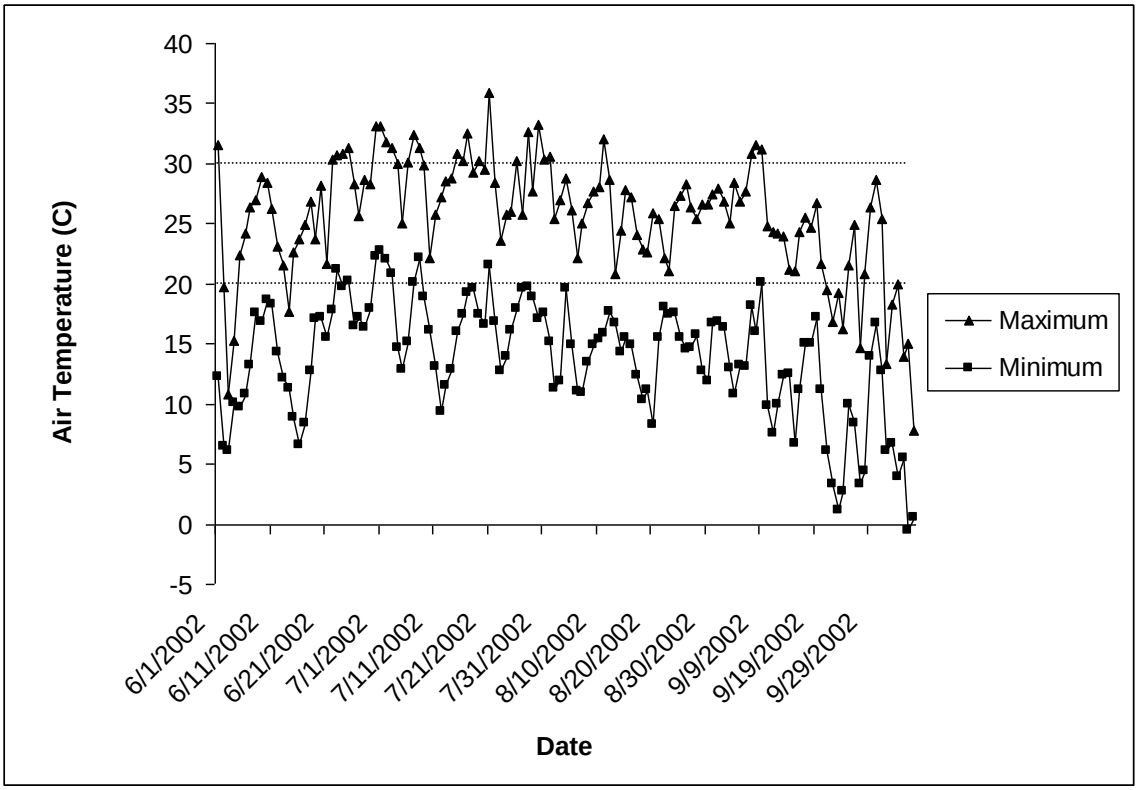
FIGURE LEGENDS

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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6/11/2002
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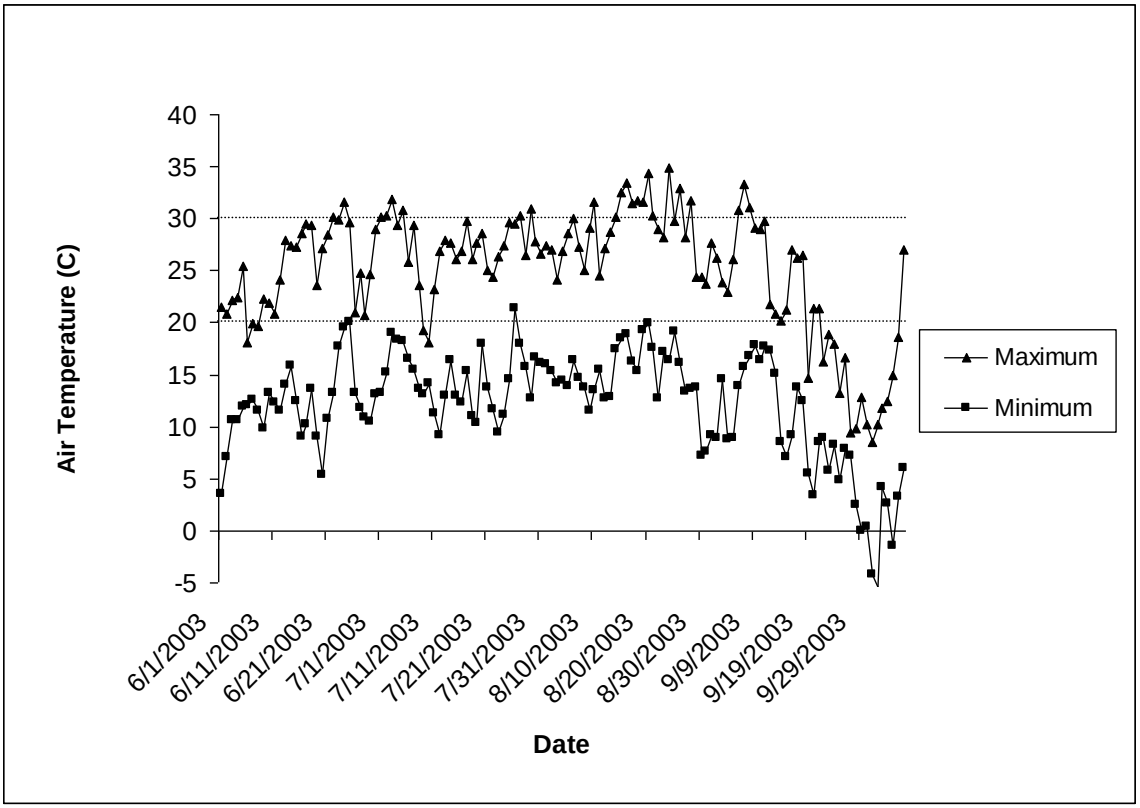
Date
Maximum
Minimum

Figure 2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Air Temperature (C)
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7/31/2003
8/10/2003
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8/30/2003
9/9/2003
9/19/2003
9/29/2003
Date
Maximum
Minimum

565

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.

Year	Source of Variation*	At Vine-kill				At Harvest				
		Sucrose		Glucose		Sucrose		Glucose		Specific Gravity
		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	<0.0001
	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

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

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			
	Sucrose		Glucose		Sucrose		Glucose	
	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			
		Sucrose		Glucose		Sucrose		Glucose	
		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			
		Sucrose		Glucose		Sucrose		Glucose	
		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			
		Sucrose		Glucose		Sucrose		Glucose	
		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 2202 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

Fry Color Research

Alvin J. Bussan
UW-Extension Vegetable Production Specialist
Horticulture Department
University of Wisconsin-Madison

Sugar End Defect

Field A Fries

3 out of 6 sugar end
stem end glucose: 0.76
bud end glucose: 0.21

Field D fries

3 out of 6 sugar end
stem end glucose: 0.948
bud end glucose: 0.325

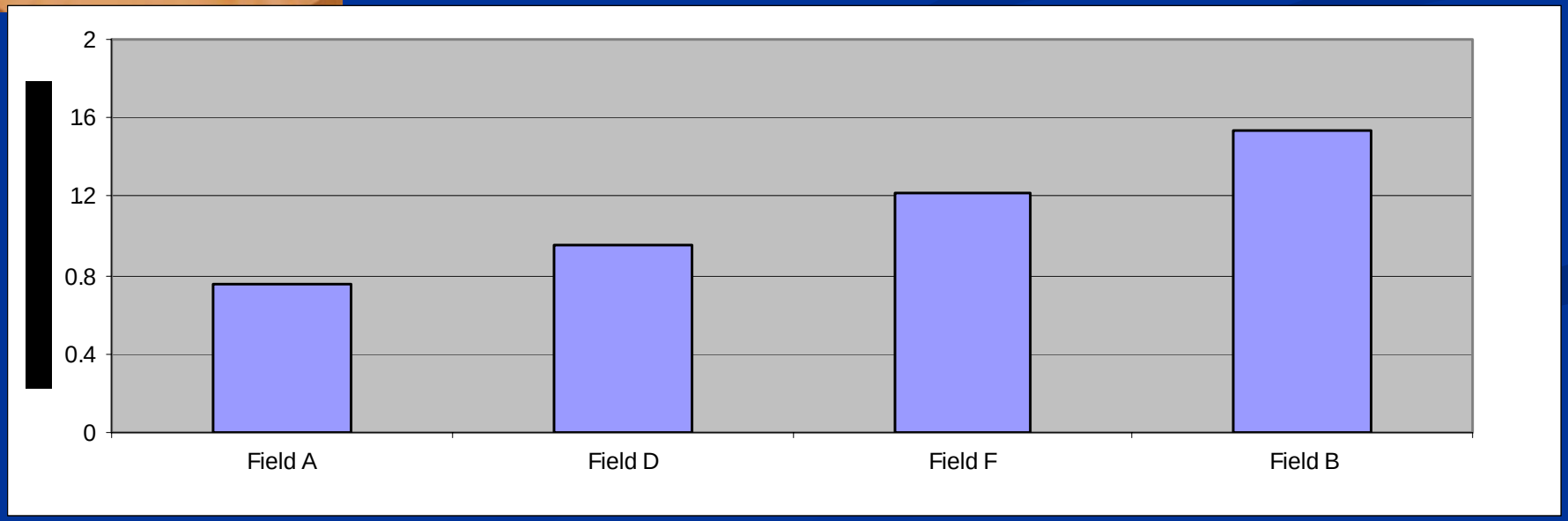
Field F fries

4 out of 6 sugar end
stem end glucose: 1.21
bud end glucose: 0.36

Field B fries

5 out of 6 sugar end
stem end glucose: 1.54
bud end glucose: 0.32

Fry Test vs. Sugars



Storage Survey Results - 2003

	Stem End		Bud end	
	glucose	sucrose	glucose	sucrose
	mg/g fresh weight			
Field A	0.76	0.335	0.212	0.371
Field B	1.543	0.484	0.319	0.467
Field C	1.074	0.369	0.306	0.335
Field D	0.948	0.441	0.325	0.363
Field E	1.19	0.329	0.347	0.296
Field F	1.217	0.49	0.364	0.417

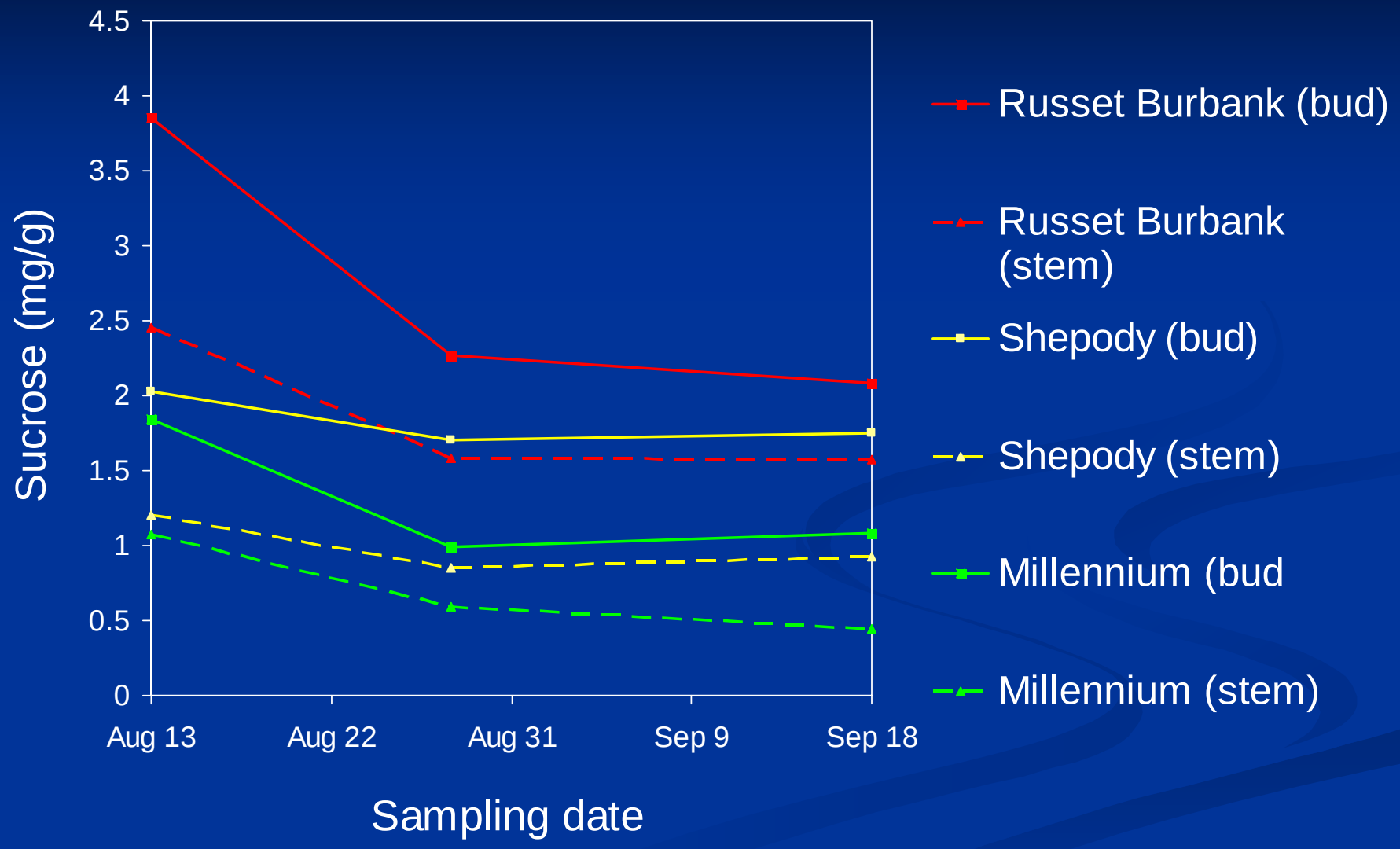
Sugar End Causes

- True sugar end
  - Activation of invertase
    - Triggered by stress
      - water
      - Heat
      - Disease??
  - Cannot recondition in storage
- Other color issues
  - Maturity
  - Other stress
  - Storage management

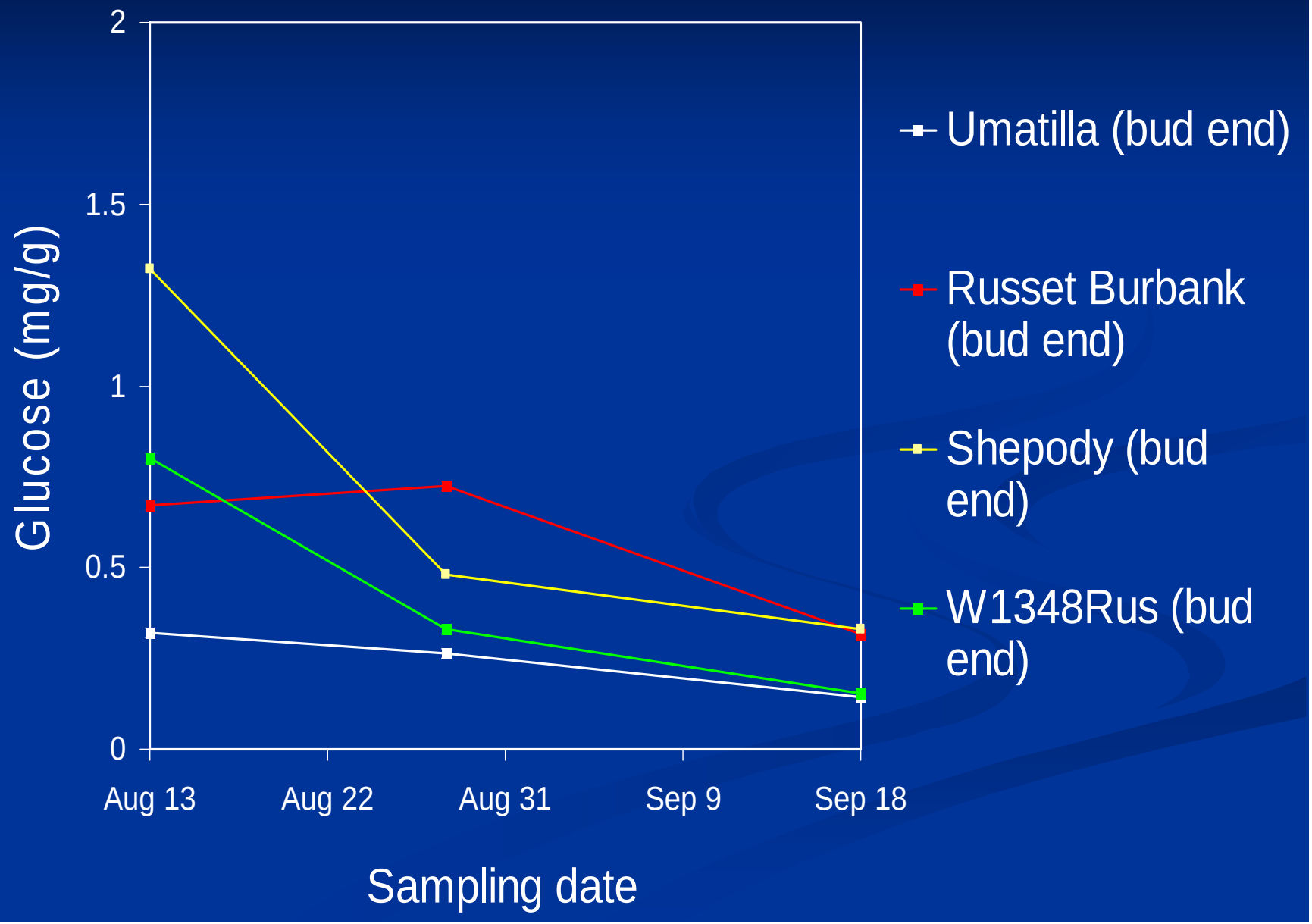
Managing Sugars in Russets

- Managing maturity
- Factors contributing to sugar end
- Irrigation management
- Managing soil temperature

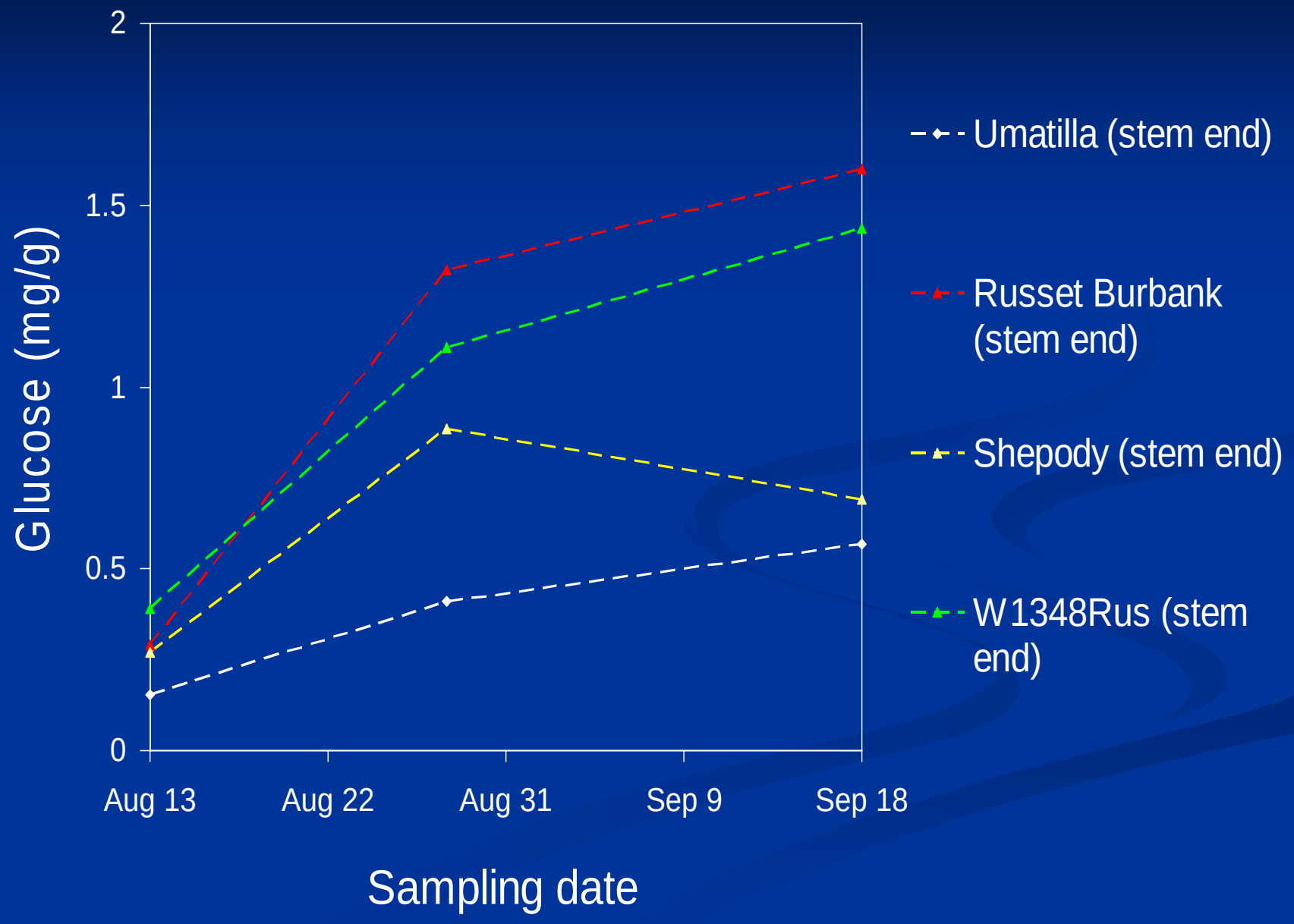
Sucrose Content over Time



Glucose Content over Time



Glucose Content over Time



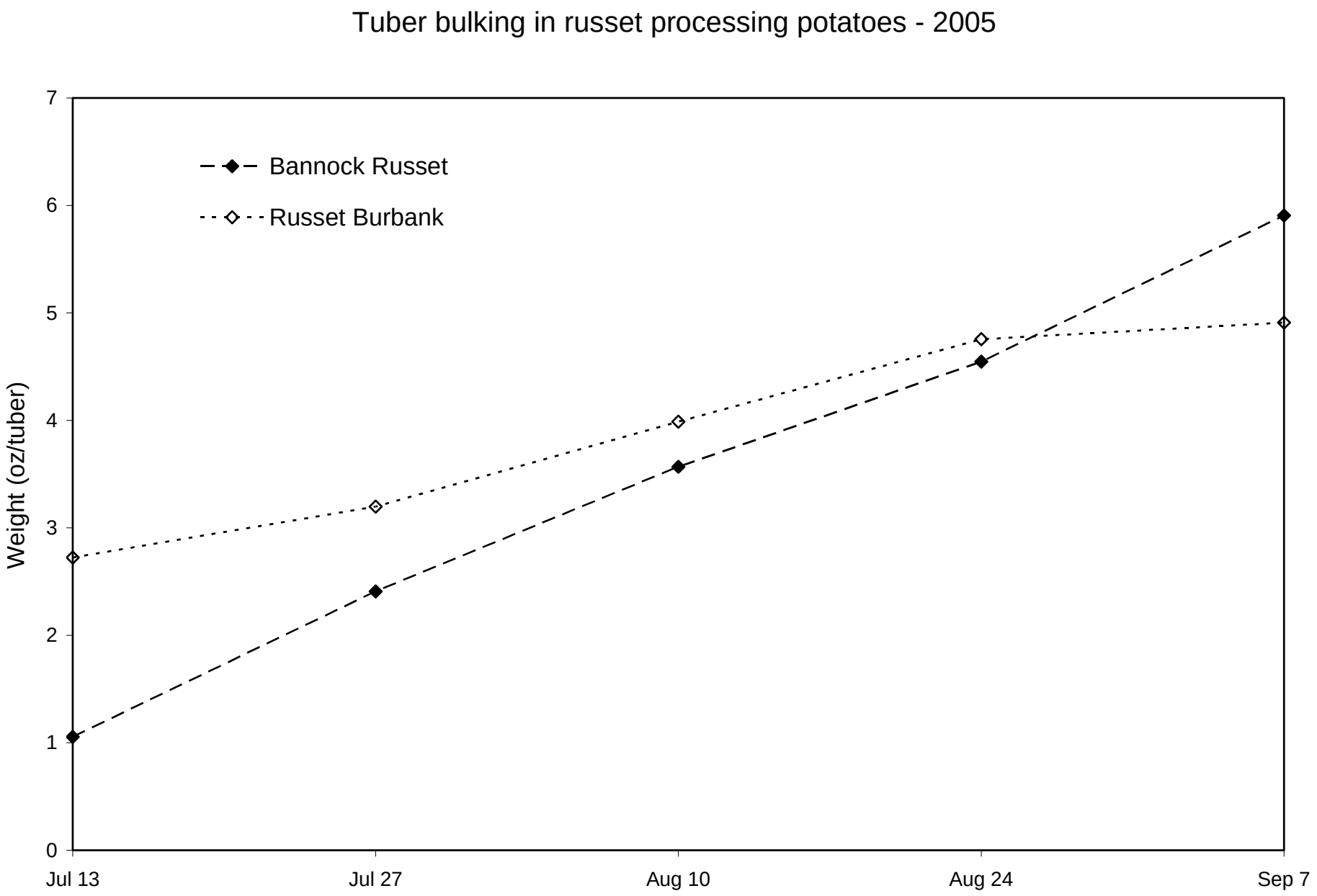

Tuber bulking in russet processing potatoes - 2005
Bannock Russet
Russet Burbank
Weight (oz/tuber)
0
1
2
3
4
5
6
7
Jul 13
Jul 27
Aug 10
Aug 24
Sep 7

Figure 1

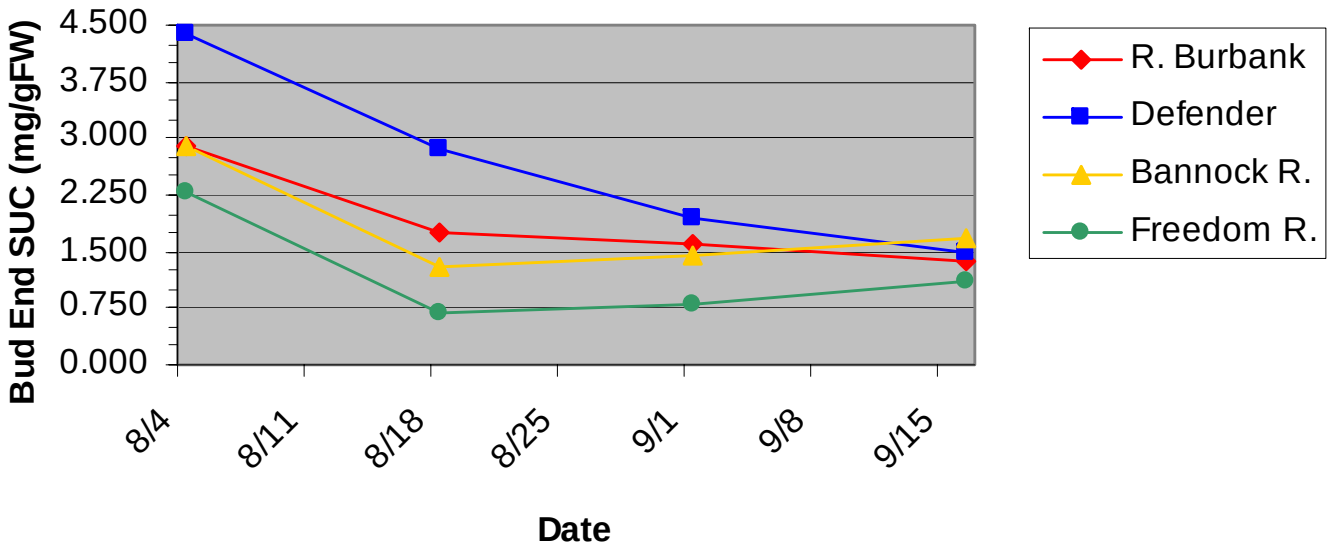
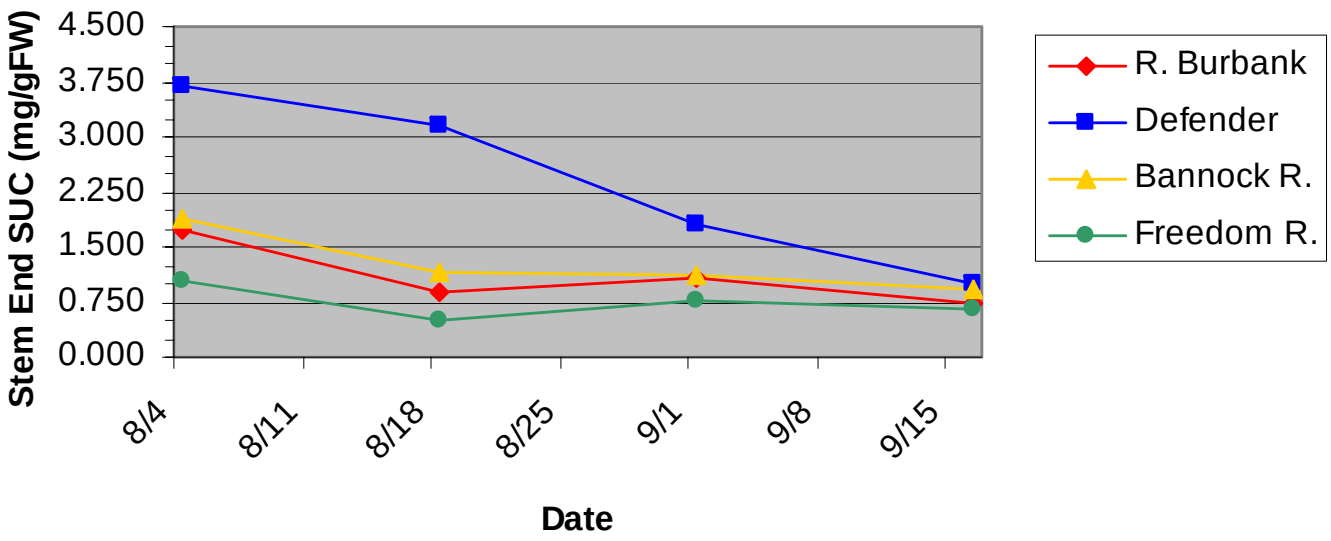
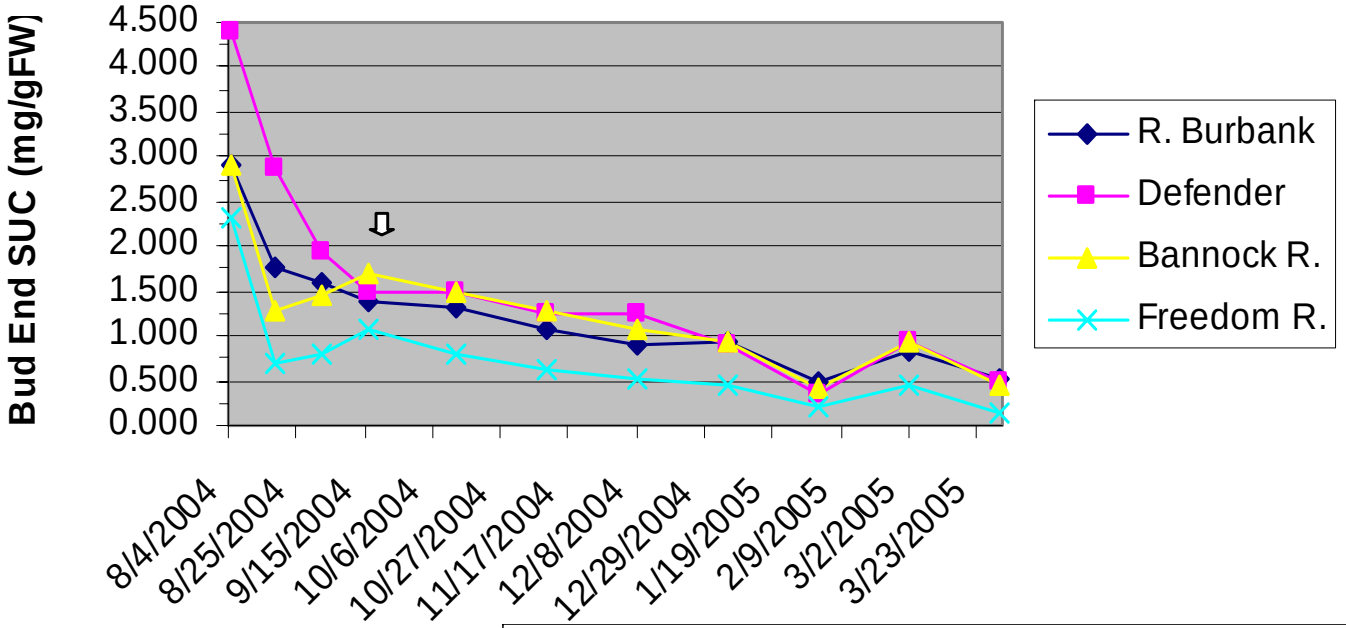
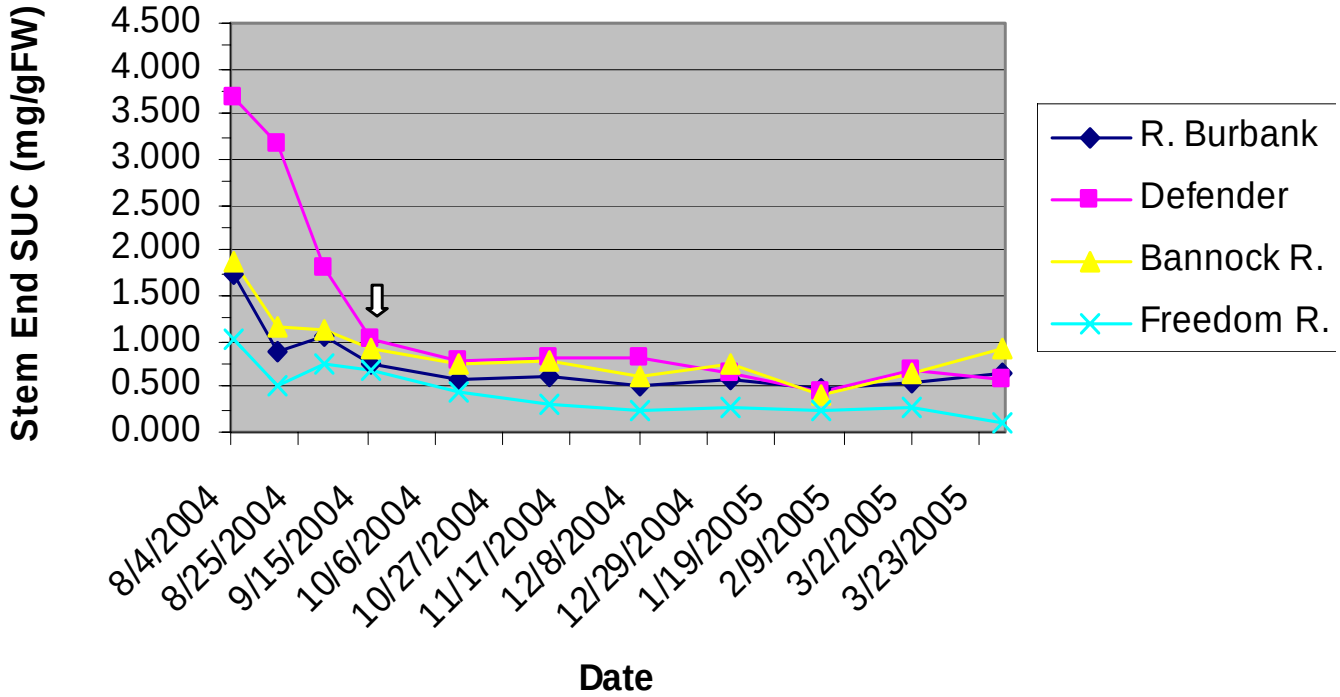


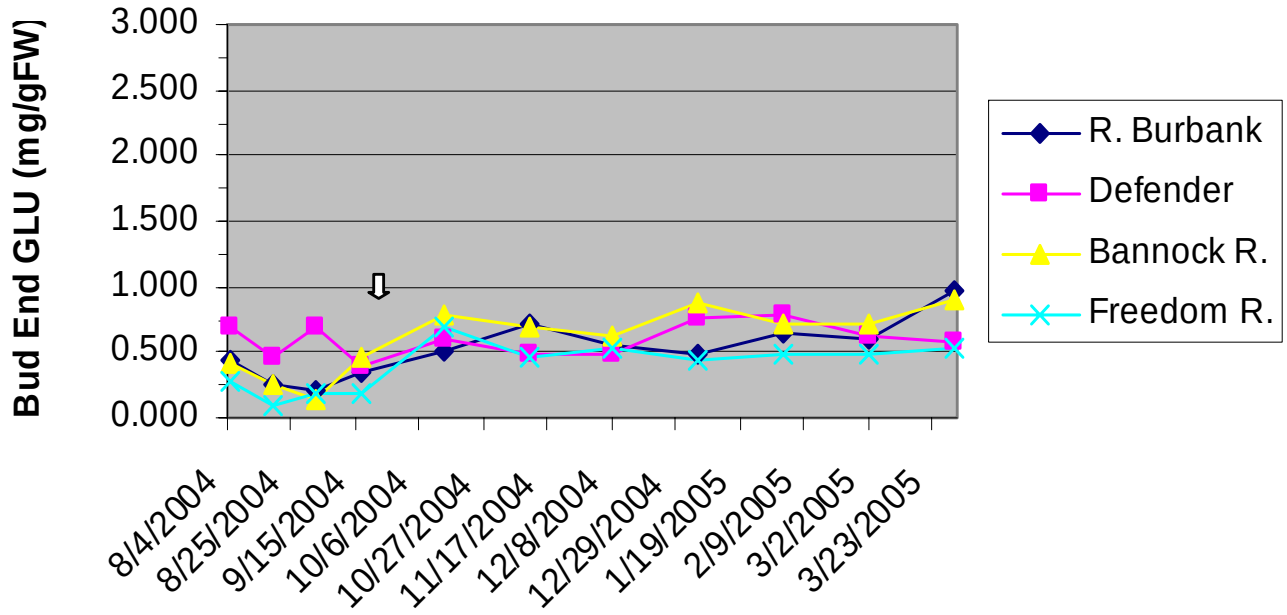
Figure 2

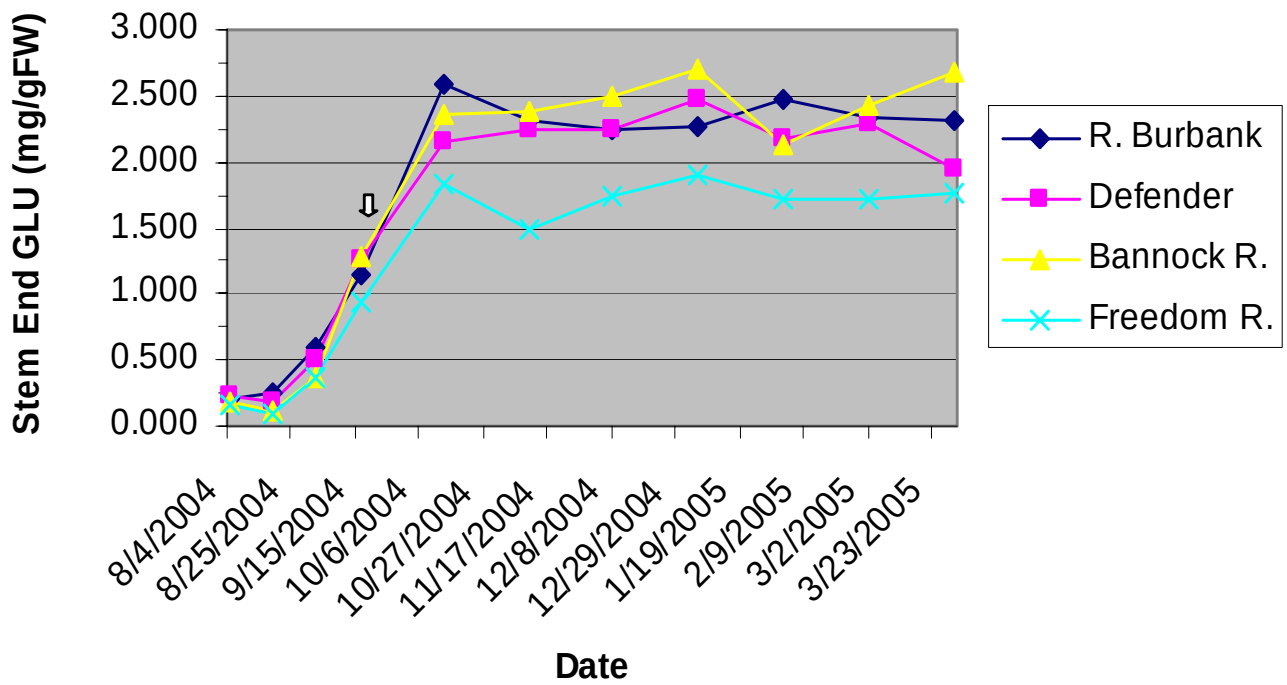


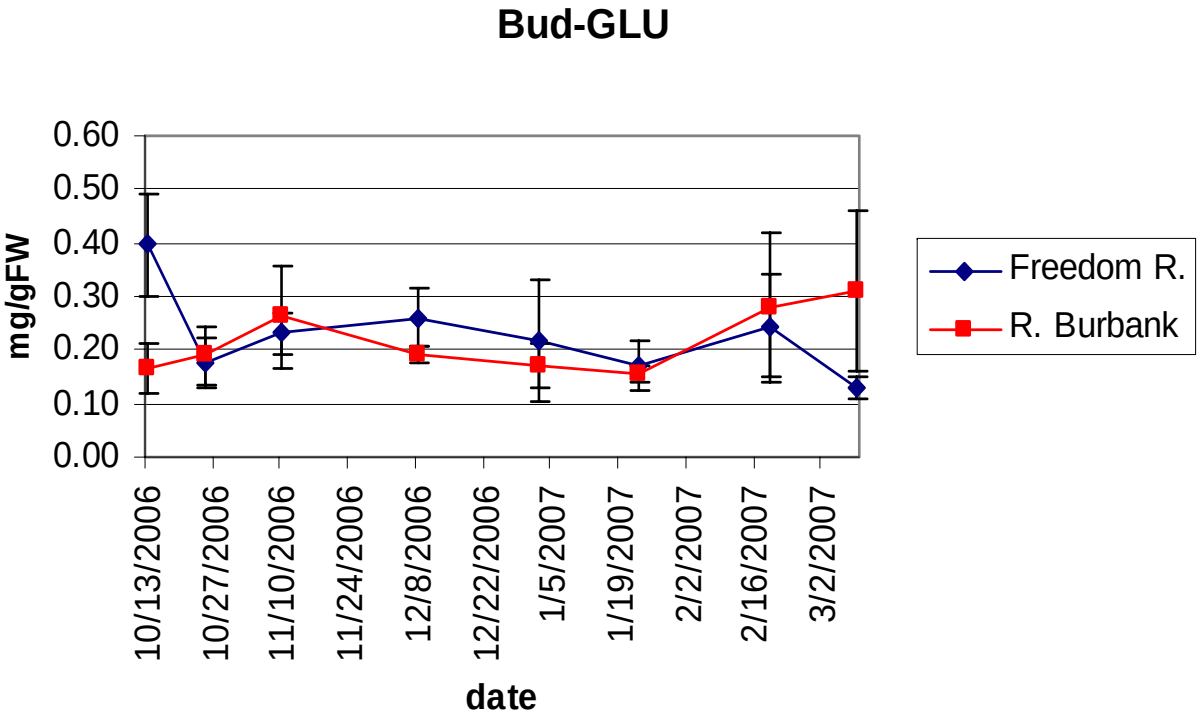
CMM Russet Potatoes

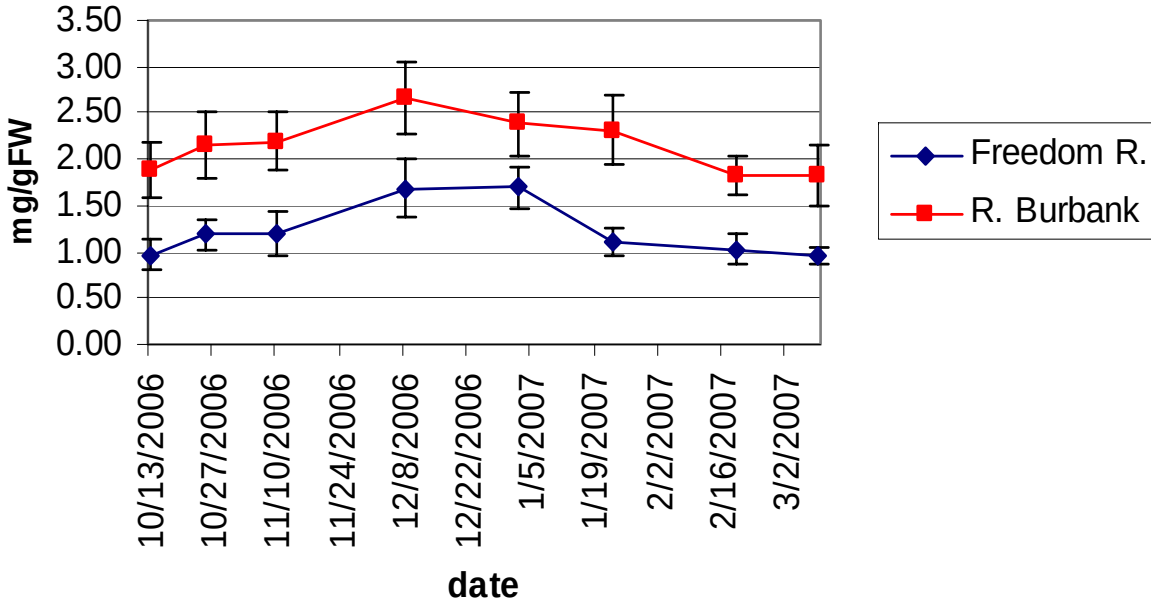

Bud End SUC (mg/gFW)
4.500
4.000
3.500
3.000
2.500
2.000
1.500
1.000
0.500
0.000
8/4/2004
8/25/2004
9/15/2004
10/6/2004
10/27/2004
11/17/2004
12/8/2004
12/29/2004
1/19/2005
2/9/2005
3/2/2005
3/23/2005
R. Burbank
Defender
Bannock R.
Freedom R.

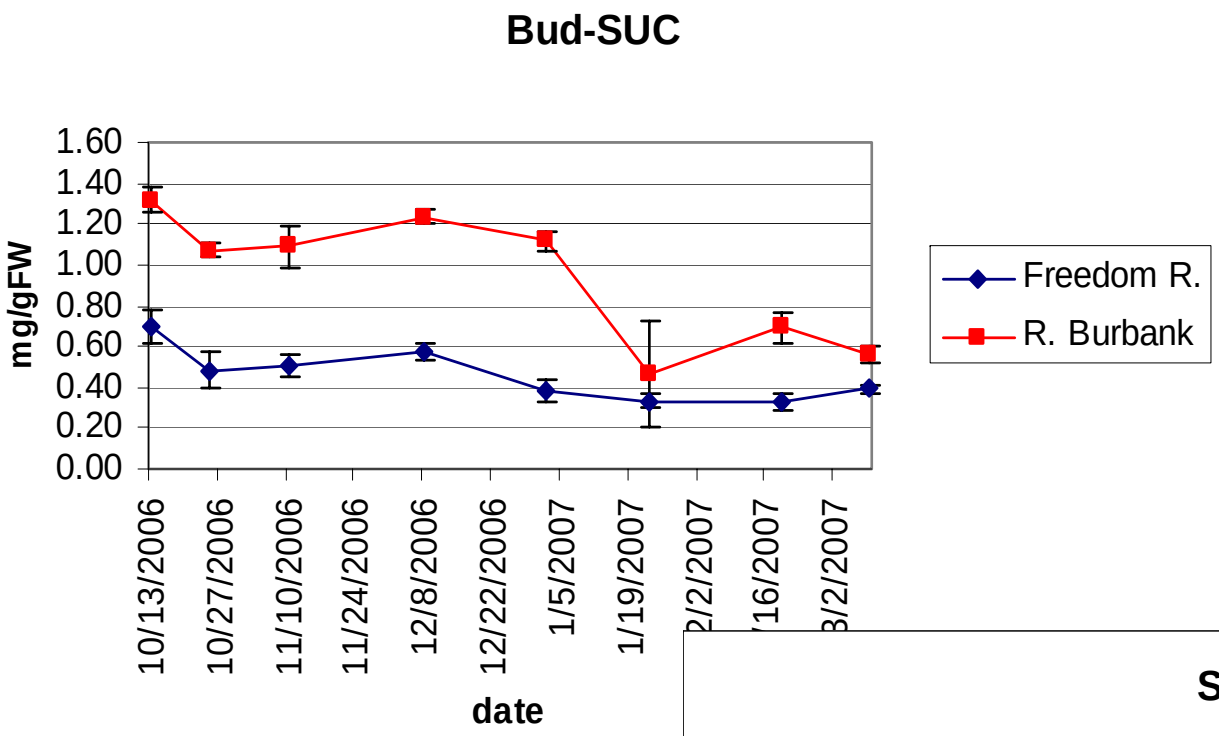

Stem End SUC (mg/gFW)
4.500
4.000
3.500
3.000
2.500
2.000
1.500
1.000
0.500
0.000
8/4/2004
8/25/2004
9/15/2004
10/6/2004
10/27/2004
11/17/2004
12/8/2004
12/29/2004
1/19/2005
2/9/2005
3/2/2005
3/23/2005
Date
R. Burbank
Defender
Bannock R.
Freedom R.

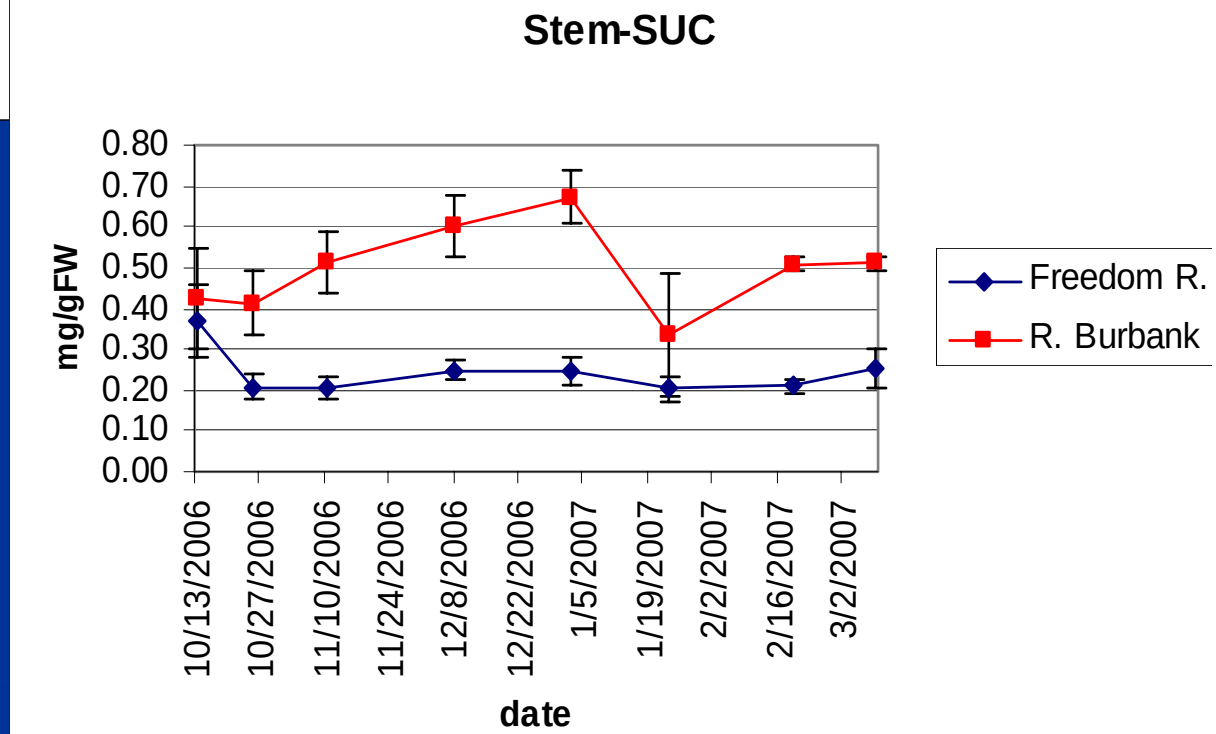

Bud End GLU (mg/gFW)
3.000
2.500
2.000
1.500
1.000
0.500
0.000
8/4/2004
8/25/2004
9/15/2004
10/6/2004
10/27/2004
11/17/2004
12/8/2004
12/29/2004
1/19/2005
2/9/2005
3/2/2005
3/23/2005
R. Burbank
Defender
Bannock R.
Freedom R.


Stem End GLU (mg/gFW)
3.000
2.500
2.000
1.500
1.000
0.500
0.000
8/4/2004
8/25/2004
9/15/2004
10/6/2004
10/27/2004
11/17/2004
12/8/2004
12/29/2004
1/19/2005
2/9/2005
3/2/2005
3/23/2005
Date
R. Burbank
Defender
Bannock R.
Freedom R.


Bud-GLU
0.60
0.50
0.40
0.30
0.20
0.10
0.00
mg/gFW
10/13/2006
10/27/2006
11/10/2006
11/24/2006
12/8/2006
12/22/2006
1/5/2007
1/19/2007
2/2/2007
2/16/2007
3/2/2007
date
Freedom R.
R. Burbank


Stem-GLU
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
mg/gFW
10/13/2006
10/27/2006
11/10/2006
11/24/2006
12/8/2006
12/22/2006
1/5/2007
1/19/2007
2/2/2007
2/16/2007
3/2/2007
date
Freedom R.
R. Burbank


Bud-SUC
mg/gFW
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
10/13/2006
10/27/2006
11/10/2006
11/24/2006
12/8/2006
12/22/2006
1/5/2007
1/19/2007
date
Freedom R.
R. Burbank


Stem-SUC
mg/gFW
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
10/13/2006
10/27/2006
11/10/2006
11/24/2006
12/8/2006
12/22/2006
1/5/2007
1/19/2007
2/2/2007
2/16/2007
3/2/2007
date
Freedom R.
R. Burbank

Managing Maturity

- Bulking stops by 9/1
- Sucrose reaches minimum concentration by 9/1
- Stem glucose increases from time 9/1 until placed in storage
- Unchanged at 55 F

Are we Managing Maturity?

- Over mature the crop
  - Timing vine-kill for storage
  - Consistency over time
- Will earlier vine – kill reduce storage sugars?
- Sugars were unchanged at 55 F in storage

Potato Physiology

Light-Engine

Potato Plant

Growth
Energy

Generator

Leaf

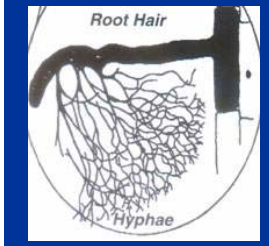
Sunlight

Chlorophyll

Carbon
Dioxide

Extra Energy

Later Root
Energy for Growth



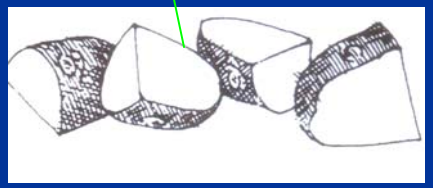
Growth Energy

Plant under stress - Growth
energy
Lack of water & Nutrients
High Temperatures

Storage Battery

Potato

Starter-Battery



Potato Seed

Vogt

Cause of Sugar End

- Identified enzymes involved
- Don't know trigger for deregulation of invertase
- Study heat and water stress at different timings on physiological processes in potato

Biotron Experiment

- Temperature effects
  - 75 standard temp
  - 85 for 5 to 7 days
- Moisture effects
  - - 25 kPa <
  - -36 kPa < x < -25 kPa
  - < -36 kPa

Measurements

- Water potential of tuber and leaf
- Osmotic potential
- Cation concentration
- Sugar concentrations
- Invertase activity
- Soil temperature and water potential

Water Relations within the Plant

		Water Potential (bars)			
		Leaf		Tubers	
Date	ET (mm)	night	day	night	day
15-Aug	4.8		-6.1		-2.2
16-Aug	3.9	-0.6	-8	-0.1	-3.2
17-Aug	3.3	-0.6	-8	-0.1	-4.2
18-Aug		-0.8		-0.2	

Gander and Tanner 1976

Temperature Effects

	Glucose (mg/g)		Sucrose (mg/g)	
Temperature	stem	bud	stem	bud
75	2.37	0.51	0.5	0.89
85	1.99	0.18	0.53	0.86

Timing of Stress

	Glucose (mg/g)		Sucrose (mg/g)	
Timing	stem	bud	stem	bud
Tuber initiation	3.5	0.32	0.53	0.97
early bulking	1.8	0.23	0.44	0.86
late bulking	2.2	0.49	0.57	0.8

Water Levels

	Glucose (mg/g)		Sucrose (mg/g)	
Water level	stem	bud	stem	bud
>65 %	2.13	0.37	0.52	0.87
>50%	2.28	0.46	0.57	0.87
<50%	2.11	0.19	0.44	0.87

Summary

- To early to draw conclusions
  - Minimize stress from the biotron
- Timing and water stress had effects
  - Temperature limited
- Water potential effects
  - Osmotic potential, cations, other solutes

Water Demand, Irrigation Need, Quality Response

- Planting
  - Soil needs to be at field capacity when planting
  - Irrigate preplant if needed during dry springs
  - Irrigating postplant & preemerge can lead to seed piece decay

Water Demand, Irrigation Need, Quality Response

- Emergence to tuber initiation – vegetative state
  - Schedule based on ET
    - ETa based on ETp corrected for canopy closure
    - Water levels below the CP can lead to losses in tuber no and leaf production
  - Good water management should ensure an LAI of at least 3 to 3.5
    - At 3 to 3.5 light interception is maximized
    - Hills covered

Water Demand, Irrigation Need, Quality Response

- Tuber initiation through early bulking
  - 3 to 5 wk period (up to 2" tubers in Russet Burbank)
  - Greatest effect on yield and quality
  - Sets the ceiling – period of cell division
  - Maintain higher water availability > 60 - 75% of plant available water if sugar end is an issue?????????
  - Daily watering in sand
  - 2-3 days in medium soils
  - Cost – disease? N - fertility

Water Demand, Irrigation Need, Quality Response

- Late Bulking
  - Water for maximum use of soil water
    - Use the entire soil profile
  - Over watering can lead to proliferation of soil born tuber disease
  - Maintain a positive water balance
  - Most likely time of heat stress
    - Transient water stress

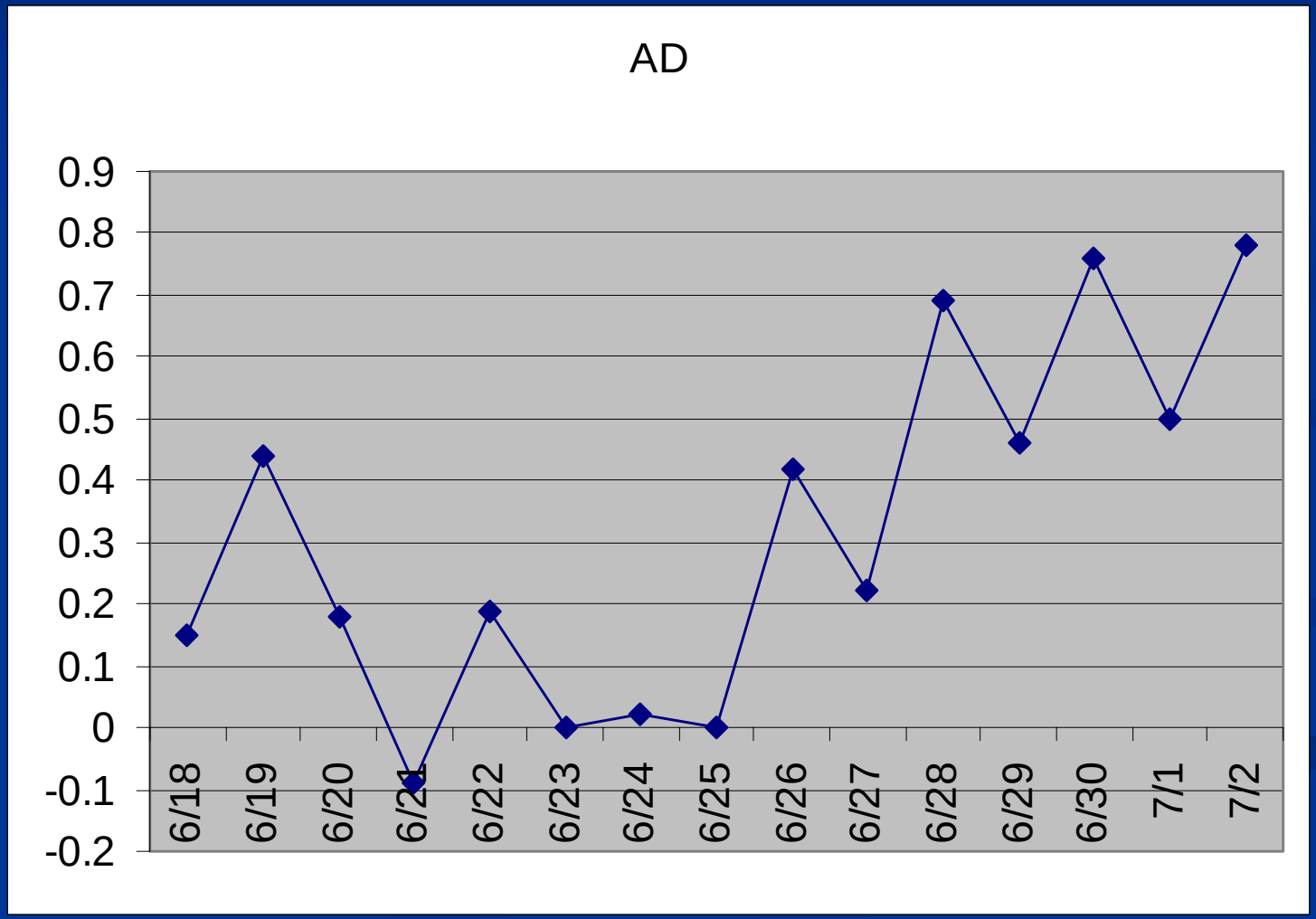
Meeting the Demands of Increased Irrigation Management

- AD Level → 50% of plant available water
  - Plainfield loamy sand: 0.10" water/1" of soil
  - 16 inch rooting depth: 16*0.1*0.5 = 0.8" of water

Date	Precip	Irrigation	Adj. ET	AD
18-Jun	0	0	0.22	0.15
19-Jun	0	0.55	0.26	0.44
20-Jun	0	0	0.26	0.18
21-Jun	0	0	0.27	-0.09
22-Jun	0	0.55	0.27	0.19
23-Jun	0	0	0.19	0
24-Jun	0.12	0.15	0.25	0.02
25-Jun	0.1	0	0.12	0
26-Jun	0	0.6	0.18	0.42
27-Jun	0	0	0.2	0.22
28-Jun	0.55	0	0.08	0.69
29-Jun	0	0	0.23	0.46
30-Jun	0	0.55	0.25	0.76
1-Jul	0	0	0.26	0.5
2-Jul	0	0.55	0.27	0.78

Potato Example
Early Bulking

AD over time

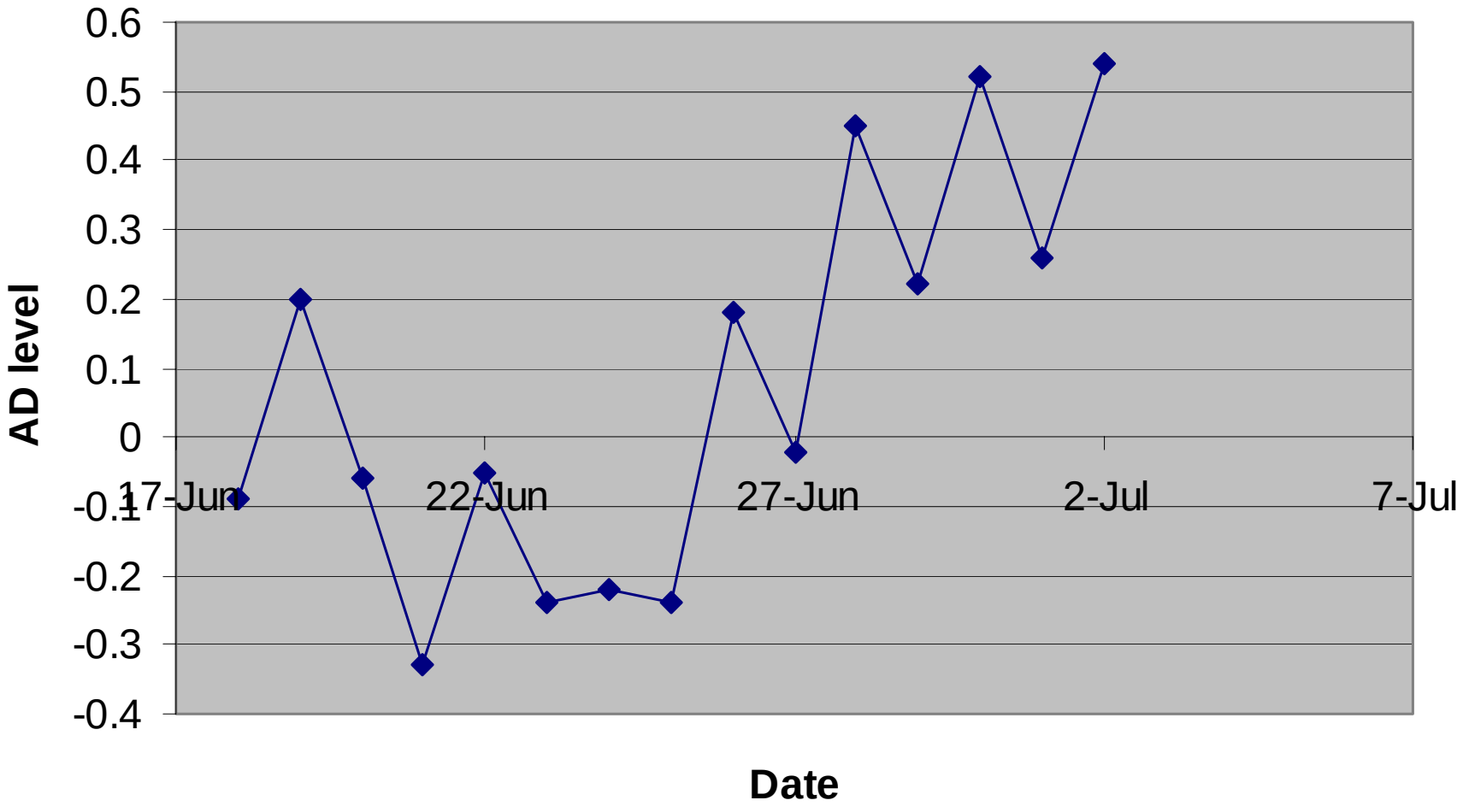

AD
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
6/18
6/19
6/20
6/21
6/22
6/23
6/24
6/25
6/26
6/27
6/28
6/29
6/30
7/1
7/2

Meeting the Demands of Increased Irrigation Management

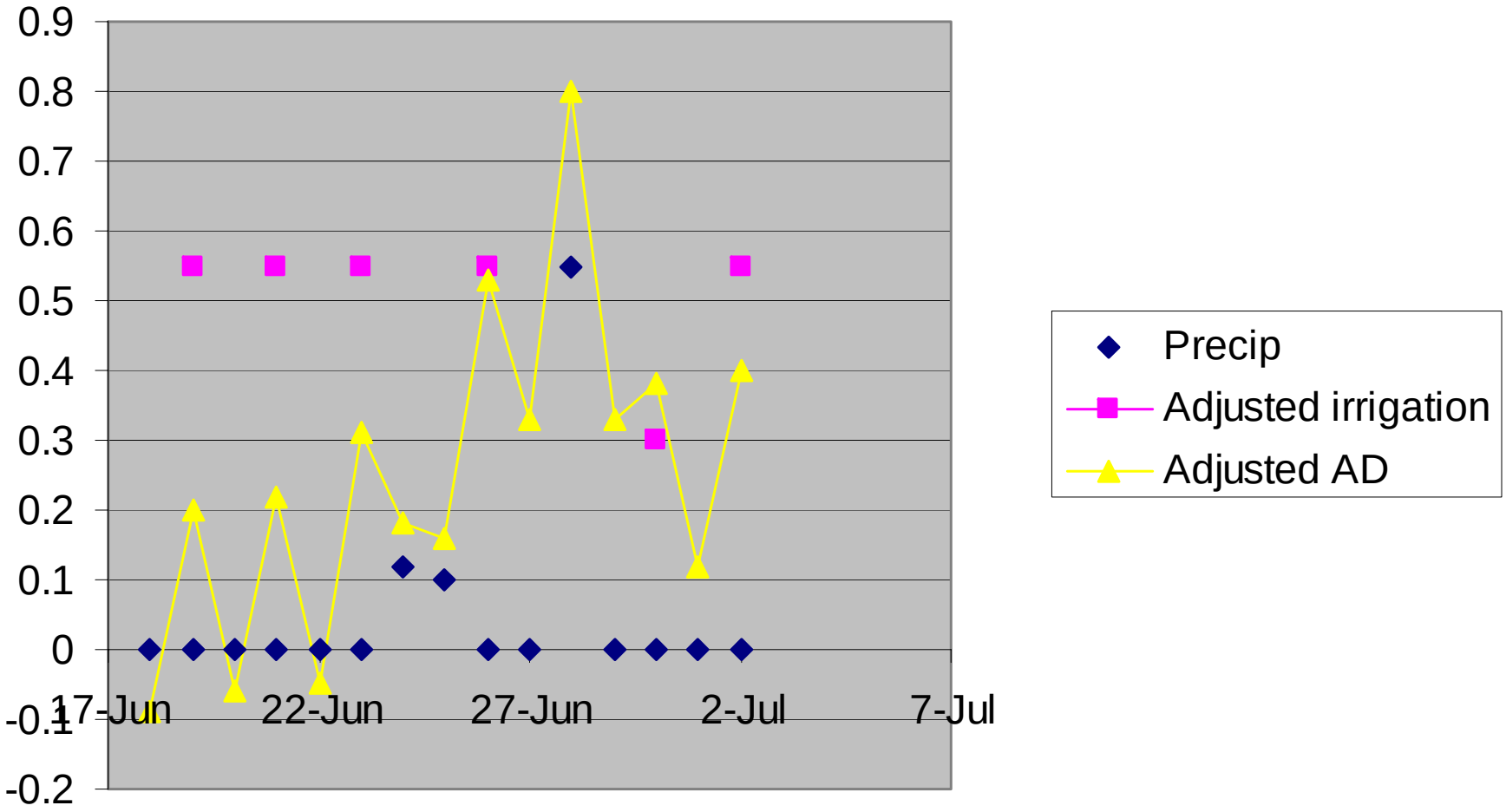
- AD Level → 50% of plant available water
  - Plainfield loamy sand: 0.10" water/1" of soil
  - 16 inch rooting depth: 16*0.1*0.5 = 0.8" of water

- AD Level → 35 % of plant available water
  - 16 inch rooting depth: 16*0.1*0.35=0.56" of water

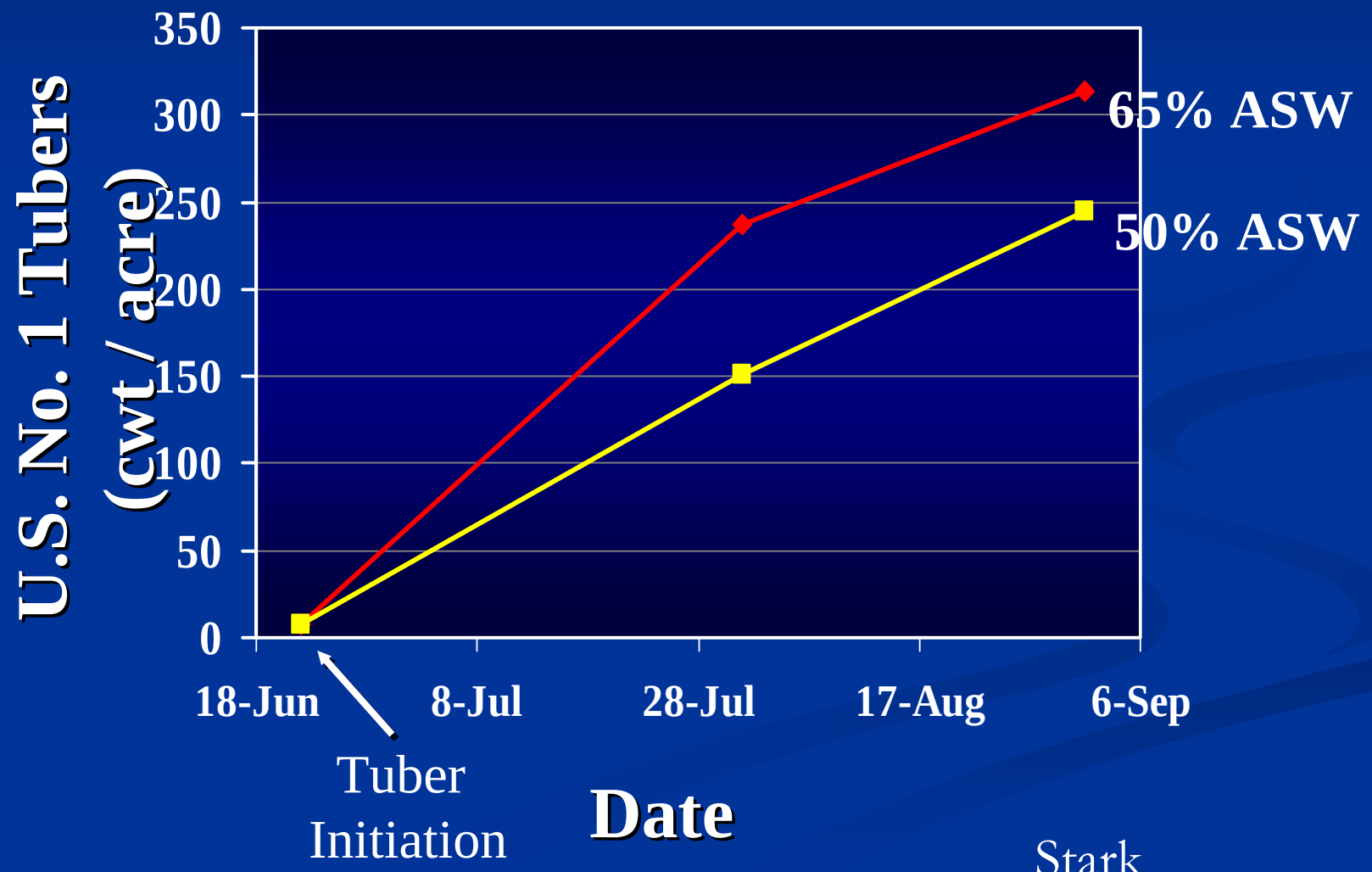
Adjusted AD


0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
AD level
17-Jun
22-Jun
27-Jun
2-Jul
7-Jul
Date

Adjusted Irrigation Schedule

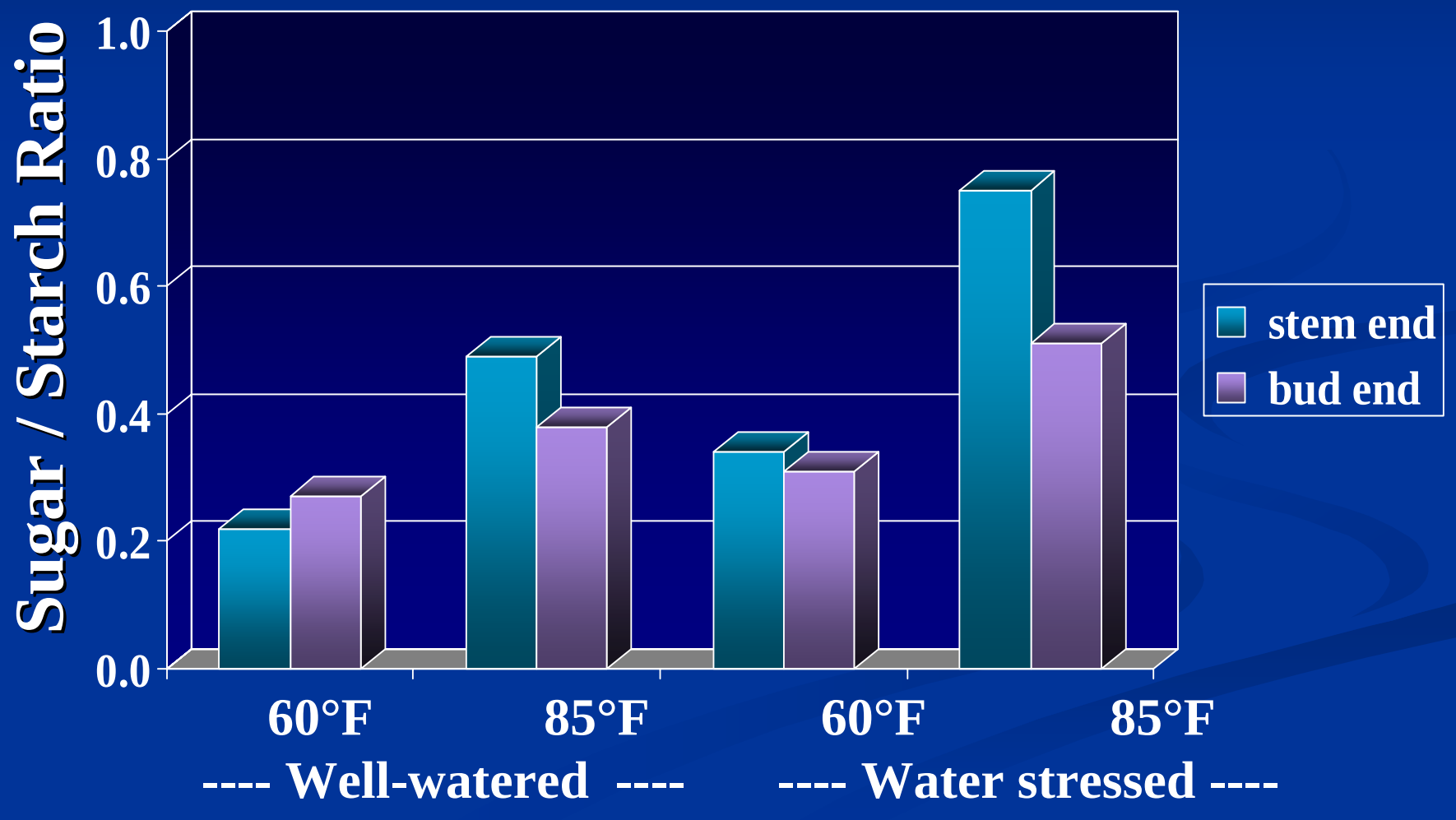


Effects of Available Water Supply on Tuber Growth of Russet Burbank Potatoes



Stark

Combined Effects of Soil Moisture and Temperature on the Sugar/Starch Ratio in the Stem and Bud ends of Russet Burbank Potatoes (Stark, et al, 1990)

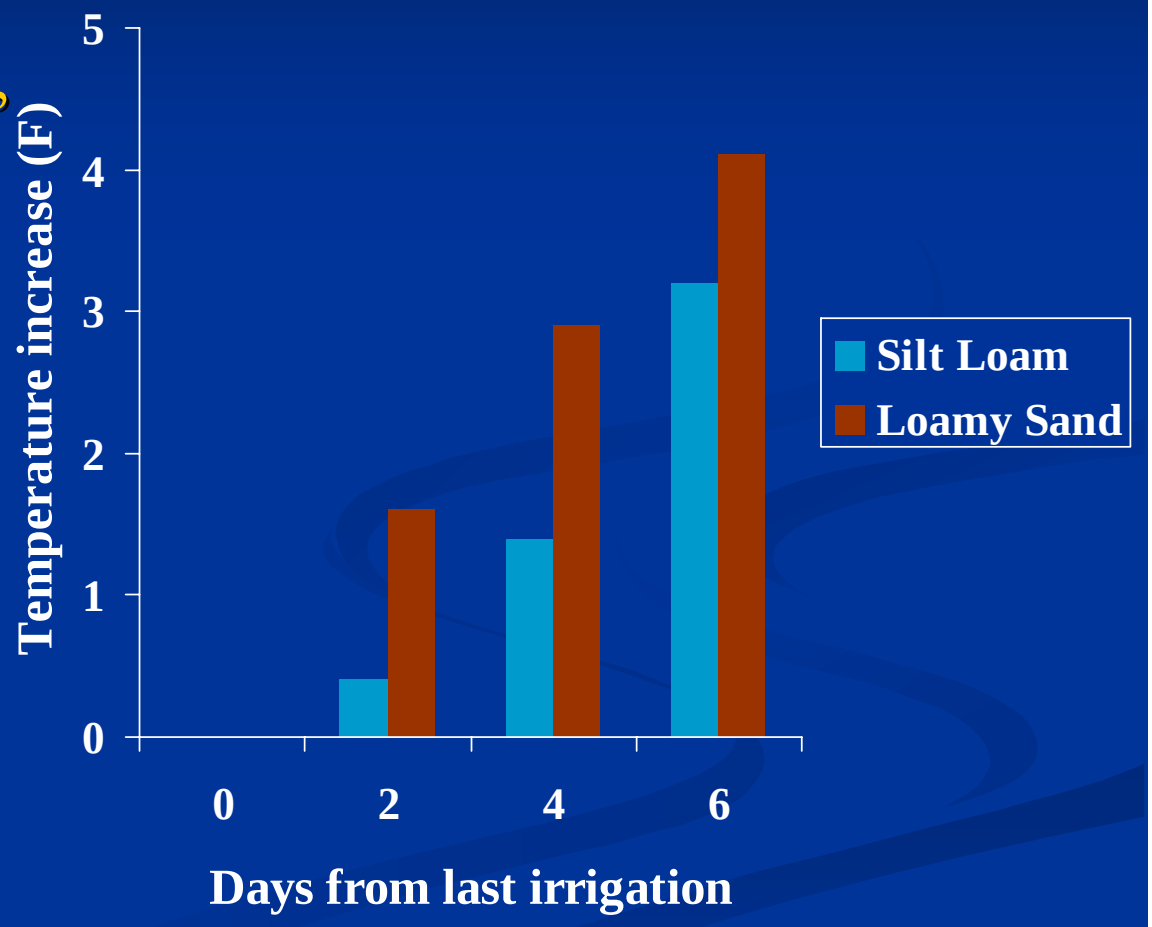


Managing Hill Temperature

- Provide canopy closure
- Irrigation management
- Hill shape
- Compaction

How does stress affect physiological processes in potato plants?

- As the soil dries out, the temperature increases



Source: Kohl, 1973

Hill Shape

Plant deeper
4 to 6” below the soil

Deep tillage
improve drainage

Increase distance from hill surfac
to tubers

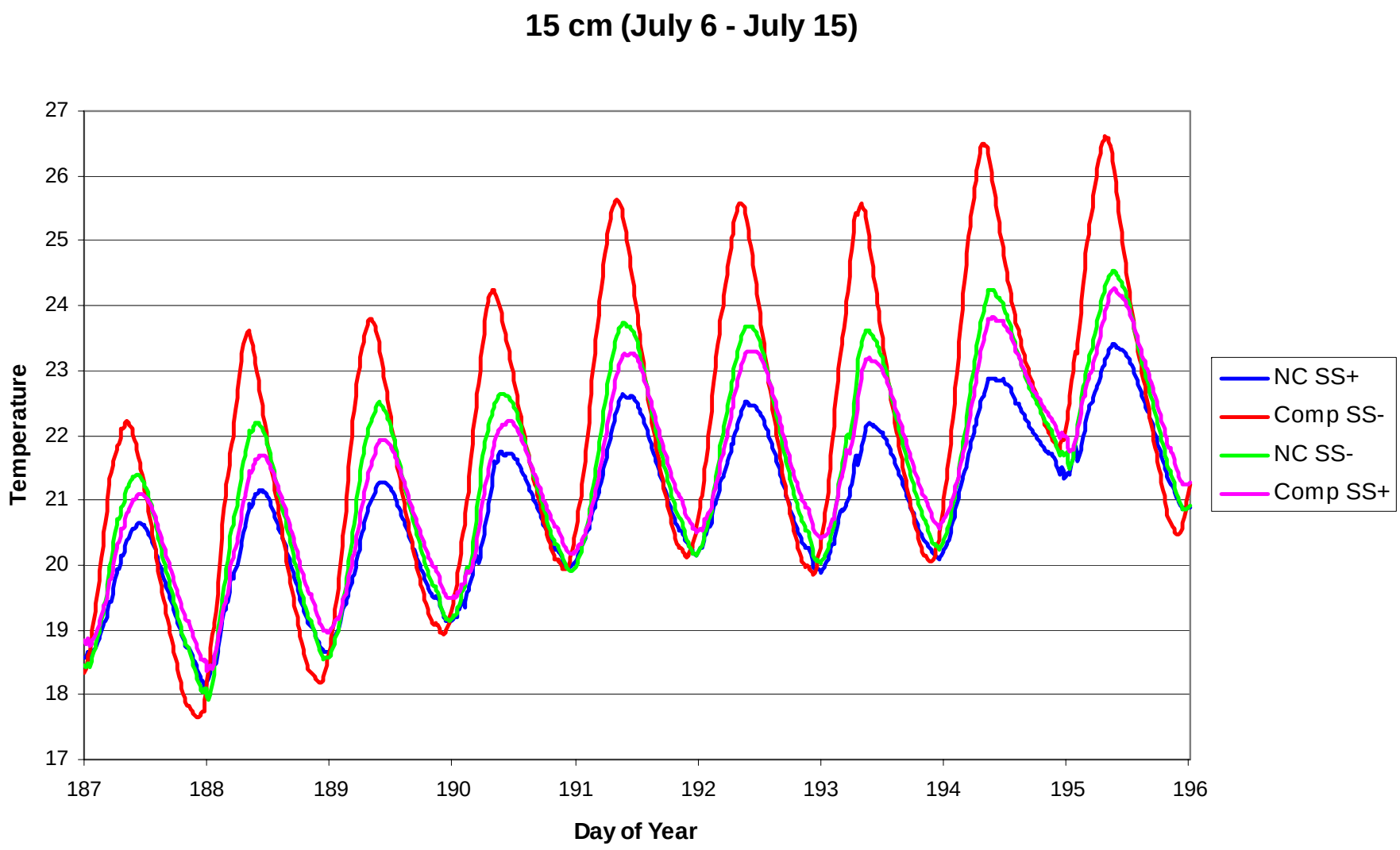
Improve water infiltration

Increased HP

TDR Probes

Deep Tillage

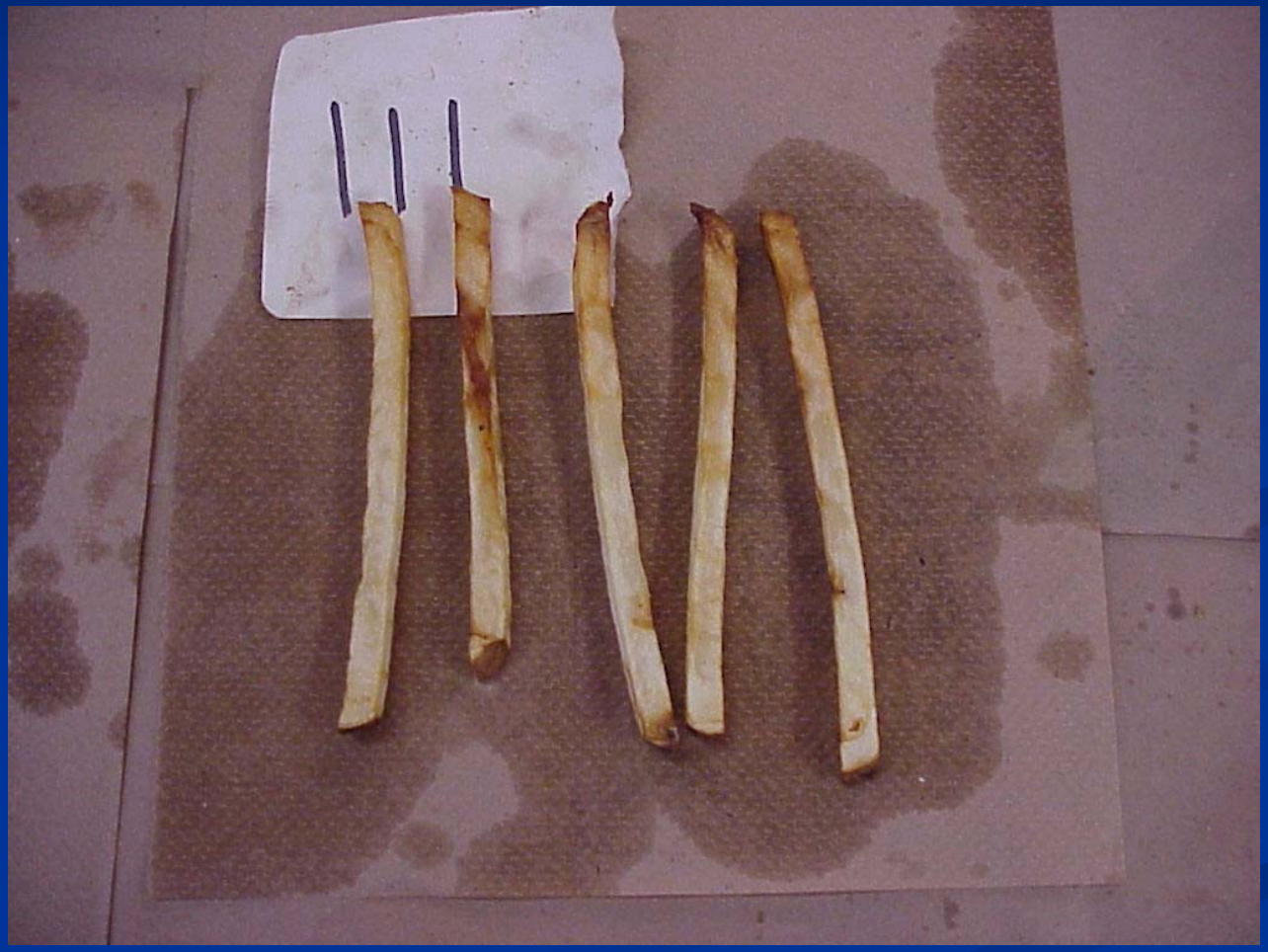
15 cm Temperatures 2005



What to Do

- Maintain healthy and uniform canopy
  - Early die leads to over maturation
- Prevent irrigation deficit
  - Especially early
  - During heat stress events
- Good loose soil
  - Deep rooting
  - Decreased hill temperature

Questions???



RESEARCH

Evaluation of the Effect of Density on Potato Yield and Tuber Size Distribution

Alvin J. Bussan,* Paul D. Mitchell, Michael E. Copas, and Michael J. Drilias

ABSTRACT

Potato (*Solanum tuberosum*) yield has been optimized for in-row spacings ranging from 15 to 40 cm depending on region, targeted market, variety, and other factors. Production goals require optimizing tuber size to maximize crop value. Our goal was to evaluate the effect of plant, stem, and tuber density on stem and tuber set, potato yield, tuber size distribution, and other quality factors. Research plots were established within a 20-ha commercial production field, and analysis was done with linear and nonlinear regression. Plant density decreased with increasing in-row plant spacing. Stem density increased linearly with increasing plant density, but response differed across years. Tuber density increased to a maximum of 190 tubers m^{-2} in response to plant and stem density, with stem density more accurately predicting tuber set. Yield was related to plant, stem, and tuber density using nonlinear regression, more accurately predicted by stem and tuber density than by plant density. A hyperbolic model was used to predict yield with estimated maximum yield of 86 Mg ha^{-1} when related to stem density. Average tuber size was related to stem and tuber density using the inverse yield law and estimated maximum average tuber size of >200 g. The distribution for tuber sizes was estimated as a Weibull probability density function that predicted changes in tuber size in response to stem and tuber density. The hyperbolic model accurately predicted tuber density and yield with the added benefit that estimated parameters have biological importance, unlike polynomial or other regression models used to predict crop yield. Modeling tuber size distribution over different stem densities provides a mechanism for future economic analysis to optimize management and conduct sensitivity analysis to determine the most important factors influencing crop value.

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A number of experiments have examined potato (*Solanum tuberosum*) yield response to planting population or in-row spacing to optimize plant population (Allen and Wurr, 1992; Arsenault et al., 2001; Creamer et al., 1999; DeBuchananne and Lawson, 1991; Love and Thompson-Johns, 1999; Lynch and Rowberry, 1977; Lynch et al., 2001; O'Brien and Allen, 1992; Rex, 1991; Sekhon and Singh, 1985; Strange and Blackmore, 1990; Wurr et al., 1990, 1992, 1993; Zebarth et al., 2006). Many of these experiments and others have also examined the effect of planting population on tuber size distribution (Allen and Wurr, 1992; DeBuchananne and Lawson, 1991; Love and Thompson-Johns, 1999; Rex, 1991; Sekhon and Singh, 1985; Strange and Blackmore, 1990; Wurr et al., 1992, 1993; Zebarth et al., 2006). The tuber size distribution is an important determinant of price. Different potato market classes have different pay scales across different tuber size categories. Contract-established prices for chip potatoes are higher for tubers with diameters between 5 and 10 cm, and processing russet potatoes received price premiums for tubers >285 g and disincentives for tubers <100 g (Creamer et al., 1999; DeBuchananne and Lawson, 1991; Love and Thompson-Johns, 1999; Schotzko et al., 1984). Fresh market potato prices are more variable over different types of potatoes and times of the years, but fresh market russets received premiums for tubers meeting specific sizes for case counts (i.e., 100–285 g), and red potatoes received price premiums for tubers <5 cm in diameter during

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different times of the year (Strange and Blackmore, 1990). Tighter margins in potato have required growers to maximize price through optimization of tuber size distribution to maximize crop value (Love and Thompson-Johns, 1999; Schotzko et al., 1984; Wurr et al., 1992, 1993).

Research on managing potato in-row spacing has focused on modeling the response of crop yield and tuber size distribution in response to crop density (Allen and Wurr, 1992; Arsenault et al., 2001; Bleasdale, 1965; Iritani et al., 1983; Knowles and Knowles, 2006; Lynch et al., 2001; Wurr et al., 1990, 1992, 1993). Polynomial regression and square root models related potato yield to crop density. Allen and Wurr (1992) identified the need for biologically meaningful models to predict crop yield response to crop density. A hyperbolic model derived from the inverse yield law was proposed as a means to predict yield response to competition (Spitters, 1983a,b; Weiner, 1982). The hyperbolic model has become a standard method of assessing the impact of weed competition on crop yield (Cousens et al., 1987; Holman et al., 2004; Jasieniuk et al., 2001). Recently, the hyperbolic model predicted wheat yield over multiple years across sites around the western United States (Holman et al., 2004; Jasieniuk et al., 2001). Yet this model has had little application in the prediction of crop yields. Potato yield was related to crop density with modified forms of the inverse yield law, but the hyperbolic function has not been used to predict potato yield response to crop density (Lynch and Rowberry, 1977).

Understanding and predicting the response of tuber size distribution to tuber, stem, or crop density has become increasingly important because of its effect on crop price. Average tuber size has been shown to decrease nonlinearly in response to increasing crop density (Allen and Wurr, 1992; DeBuchananne and Lawson, 1991; Iritani et al., 1983; Knowles and Knowles, 2006; Travis, 1987; Wurr et al., 1992, 1993; Zebarth et al., 2006). Similar to crop yield, quadratic and square root models were used to relate average tuber size and crop density in potato (Knowles and Knowles, 2006; Wurr et al., 1992, 1993). The inverse yield law predicted response of average yield or biomass per plant to increasing crop density (Harper, 1965; Holliday, 1960; Lynch and Rowberry, 1977; Spitters, 1983a; Weiner, 1982). Changes in average tuber size in response to increasing density had a similar pattern to average plant yield or biomass (Allen and Wurr, 1992, Knowles and Knowles, 2006; Lynch and Rowberry, 1977). The inverse yield law may predict average tuber size, with the added benefit that estimated parameters have biological significance, such as maximum average tuber size (Holliday, 1960; Weiner, 1982). However, potato crop price was influenced by the proportion of tubers in multiple size categories, not just the average tuber size. To predict crop value, methods of predicting changes in the tuber size distribution were necessary (Allen and Wurr, 1992; Knowles and Knowles, 2006; Love and Thompson-Johns, 1999; Rex, 1991; Strange and Blackmore, 1990; Wurr et al., 1990, 1992, 1993). Normal distributions have been used to estimate the distribution of tuber sizes to increasing potato density (Travis, 1987; Wurr et al., 1992). However, most potato size distributions do not have a normal distribution, limiting the utility of this approach for predicting tuber size distribution (Knowles and Knowles, 2006; Love and Thompson-Johns, 1999; Rex, 1991; Sekhon and Singh, 1985; Strange and Blackmore, 1990).

The importance of managing crop density to optimize potato yield and tuber size distribution should be evident, but the appropriate measure of crop density in potato has been debated. Plant density (in-row spacing) seems a logical measure of crop density. However, predictions of potato yield response to plant density have been limited due to variability in yield components within and across multiple experiments (Allen and Wurr, 1992; Bleasdale, 1965; Hammes, 1985; Lynch and Rowberry, 1977; Lynch et al., 2001; Wurr et al., 1990, 1992, 1993). Differences in potato seed production, seed size, and handling have affected stems and tubers per plant within a common variety and contributed to variability in crop yield response to plant density (Bleasdale, 1965; Iritani et al., 1983; Knowles and Knowles, 2006; Knowles et al., 1985; Lynch and Rowberry, 1977; Lynch et al., 2001; O'Brien and Allen, 1992; Sekhon and Singh, 1985; Strange and Blackmore, 1990; Wurr et al., 1990, 1992, 1993). Stem density predicted potato crop yield better than plant density, in part because stem density predicted tuber density more accurately than plant density (Allen and Wurr, 1992; Bleasdale, 1965; De la Morena et al., 1994; Lynch et al., 2001; Wurr et al., 1990; Zebarth et al., 2006). In addition, stems per plant have not been influenced by plant density but by physiological factors resulting from the management of the seed (Allen and Wurr, 1992; De la Morena et al., 1994; Iritani et al., 1983; Knowles and Knowles, 2006; Knowles et al., 1985; Love and Thompson-Johns, 1999; O'Brien and Allen, 1992; Rex, 1991; Wurr et al., 1990). As a result, research efforts have focused on identifying methods to manage stem density by seed manipulation and optimal crop planting rates based on anticipated stem production per seed piece. Tubers per plant changed with increasing plant or stem density, making management of tuber density dependent on the predicted response to increasing stem or plant density (Allen and Wurr, 1992; Bleasdale, 1965; De la Morena et al., 1994; Hammes, 1985; Iritani et al., 1983; Knowles and Knowles, 2006; Lynch et al., 2001; Love and Thompson-Johns, 1999; O'Brien and Allen, 1992; Rex, 1991; Wurr et al., 1990, 1992, 1993; Zebarth et al., 2006). In addition, assessing and hence managing tuber density requires destructive plant sampling, further increasing the difficulty of manipulation. Ultimately, the high correlation between stem and tuber

density has allowed prediction of tuber density and ultimately yield with stem density (Allen and Wurr, 1992; Bleasdale, 1965; De la Morena et al., 1994; Hammes, 1985; Lynch et al., 2001; Knowles and Knowles, 2006; Wurr et al., 1990, 1992, 1993).

The goal of this project was to quantify effects of crop density on potato tuber yield and the tuber size distribution. Specific objectives were (i) to identify the influence of in-row spacing between seed pieces on stem and tuber density, (ii) to quantify the crop yield response of potato to plant, stem, and tuber density, and (iii) to quantify the response of average tuber size and the tuber size distribution to stem and tuber density.

MATERIALS AND METHODS

Field-scale experiments were conducted during 2002 and 2003 to evaluate the influence of changing potato planting population on stem and tuber set, potato yield, and tuber size distribution. Experiments were conducted on Coloma Farms, near Coloma, WI. Research fields were planted for production of 'Russet Burbank' potatoes and for their proximity to the University of Wisconsin–Madison, Hancock Agricultural Research Station (latitude: 44°8′23″ N; longitude: 89°31′23″; elevation: 328 m). The soil type was Plainfield loamy sand (sandy, mixed, mesic, Typic Udipsamments). The experimental design was a randomized complete block with six replications. Treatments included three different planting rates. A commercial 12-row planter was preset to plant seed pieces at 30-, 40-, and 50-cm spacings within the row. The size of the experimental field was 16 ha each year of the experiment. Each plot was 18 m wide (two passes with the potato planter) and 400 m long. Subplots were established at four distinct locations across the length of the plot following emergence. Each subplot included five plants, and the distance between the first and fifth plant was recorded to allow for calculating density. Sprayer track lanes and center pivot irrigation wheel tracks had highly variable microclimates and severe compaction and were avoided when establishing subplots. Experimental measurements were collected within each subplot.

Field corn was the previous crop, and Russet Burbank was the potato variety planted across the entire field each year. Crop management strategies used at each site were based on recommendations developed at the University of Wisconsin–Madison (Boerboom et al., 2006; Kelling et al., 1998). Fields were prepared for planting by spring subsoil tillage before the 2002 experiment and fall subsoil tillage before the 2003 experiment. Final tillage was completed with a soil finisher. Seed tubers were machine cut into 65- to 75-g pieces and suberized for 3 to 5 d before planting. Plots were machine planted at a depth of 12 to 15 cm, and seed spacing was set according to treatment in rows spaced 75 cm apart on 20 Apr. 2002 and 25 Apr. 2003. Fertilizer applications were based on soil and plant tissue analysis following standard practices for Russet Burbank potatoes in central Wisconsin. Hilling was completed just before crop emergence with a disk hiller, resulting in standard flat hills in 2002. The hilling operation was completed with a rotating blade reservoir hiller in 2003. Supplemental irrigation was applied with a center pivot and typically started in early June and continued through early September following vine desiccation. Irrigation and timing were based on a scheduling program that used estimates of evapotranspiration and precipitation.

Final harvest was coordinated with the cooperating grower, and all subplots were hand harvested before field digging operations. Plots were hand dug between the third and fourth week of September, depending on the timing of vine desiccation. The total number of stems and tubers was recorded for each five-plant subplot at harvest. The length of subplot and row width were used to calculate plant, stem, and tuber density. Hand harvesting was done to ensure accurate assessment of stem and tuber counts and to ensure harvest of all tubers. Harvested subplots were graded at the University of Wisconsin–Madison Hancock Agricultural Research Station for yield and tuber distribution. Tubers were washed and graded according to industry size categories: less than 113, 113 to 170, 170 to 284, 284 to 369, 369 to 454, and greater than 454 g. B-sized potatoes (tubers <4.75 cm in diameter) and cull potatoes (including rotted, off-shaped, growth cracked, sunburned, and green tubers) were removed and weighed separately before size grading. The average weight of B-sized tubers was 84 g as determined by four lots of 100 tubers.

Data Analysis

The data were subjected to linear and nonlinear regression analysis. Lack-of-fit tests were used to determine if nonlinear models improved predictability in the data compared with linear models. Data were then subjected to a modified Levene's test (Neter et al., 1996) to assess homogeneity of error variances between years before combining data. In addition, before combining data, parameter estimates were compared across years and F tests were completed to determine if analysis by year described more of the data than combined analysis. Linear regression was used to relate plant density to in-row spacing and stem density to plant density Tuber density was related to plant and stem density with nonlinear regression. Crop yield was related to plant, stem, and tuber density with nonlinear regression as well. A hyperbolic model was used to predict tuber density and crop yield (Eq. [1]) (Cousens et al., 1987, Jasieniuk et al., 2001):

$$Y = i \star N/(1 + i \star N/a) \quad [1]$$

where Y is tuber density or yield; i is initial slope of the curve and represents the tubers or yield per plant, stem, or tuber at low density and in the absence of intraspecific competition; N is the density of plants, stems, or tubers per square meter; and a is the upper asymptote and represents the maximum tuber set or yield. Average tuber size was related to stem and tuber density with nonlinear regression. A modified version of the inverse yield law was used to predict average tuber size (Eq. [2] and [3]) (Holliday, 1960; Spitters, 1983a; Weiner, 1982):

$$1/\bar{R}_t = 1/R_{max} + b \star N \quad [2]$$

$$\bar{R}_t = R_{max}/(1 + c \star N) \quad [3]$$

where $\bar{R}_t$ is the average tuber size, R_{max} is the maximum tuber size in the absence of intraspecific competition, and b and c represent the change in average tuber size with change in density.

The distribution for the size of potato tubers was modeled as a probability density function with parameters depending on

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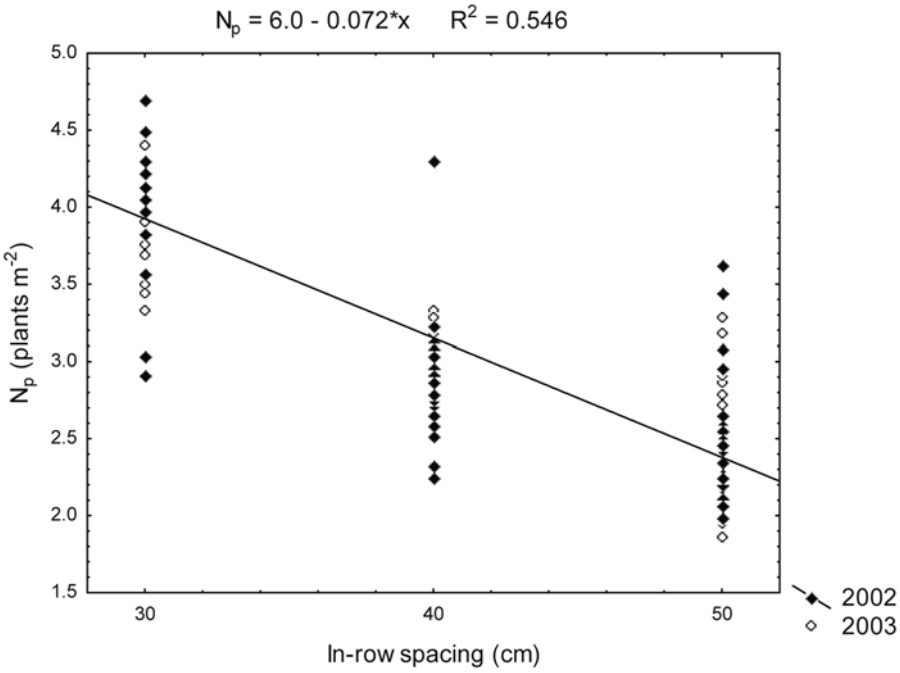

Figure 1. Influence of in-row spacing on potato plant population near Coloma, WI, in 2002 and 2003.

tuber or stem density. Parameters describing tuber size distribution were estimated by fitting a cumulative distribution function to observed accumulated proportion of tubers in each size category. A Weibull distribution was used because it was strictly positive and sufficiently flexible to be skewed left or right or to be symmetric (Evans et al., 2000). For a random variable R_t with a Weibull distribution, the probability density function $f(R_t)$ and the cumulative distribution function $F(R_t)$ were

$$f(R_t) = \alpha \star R_t^{\alpha-1} \star \exp\left(-(R_t/\beta)^{\alpha}\right)/\beta^{\alpha} \quad [4]$$

$$F(R_t) = 1 - \exp\left[-(R_t/\beta)^{\alpha}\right] \quad [5]$$

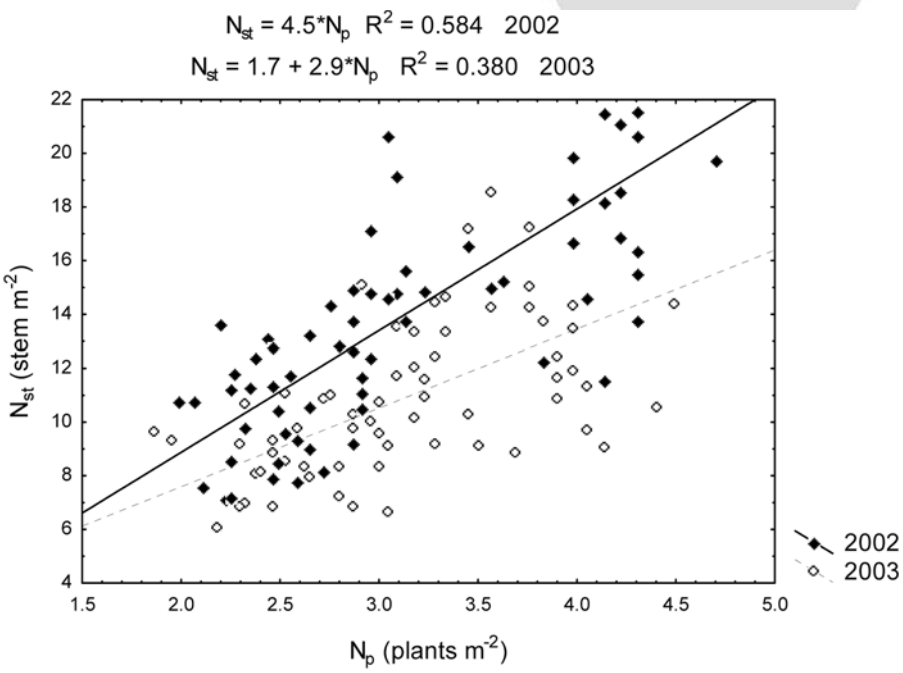

Figure 2. Response of potato stem density to potato plant density in commercial production field during 2002 and 2003 near Coloma, WI.

where the parameters α and β are strictly positive (Evans et al., 2000).

The cumulative distribution function (Eq. [5]) was fit to observed data using least squares to estimate the parameters α and β. The effect of tuber density or stem density was captured by estimating the parameters α and/or β as functions of these measures. Several equations for α and β as functions of N_t, tuber density, or N_{st}, stem density, were estimated. Based on the R-squared, the best model directly estimated α and fit the following exponential model for β:

$$\beta = \exp(\beta_0 + \beta_1 \star N) \quad [6]$$

where N is either N_t for tuber density (tubers m^{-2}) or N_{st} for stem density (stems m^{-2}).

RESULTS

In-row spacing of plants effectively altered plant density across both years (Fig. 1). Plant density varied within treatments even though the planter was set to deliver predetermined in-row spacings of 30, 40, and 50 cm. The range in minimum to maximum density around each row spacing treatment was 2 plants m^{-2} centered on the average density targeted for the treatment. Total range in plant density resulting from the treatment was between 2.0 to 4.5 plants m^{-2} or 20,000 to 45,000 plants ha^{-1}. Plant densities listed assume each hill was planted to a single seed piece and that two plants were not growing together. The grower used a mechanical pick planter to minimize the number of doubles in each hill. The number of doubles could not be confirmed without destructively sampling the hills after planting.

Stem density was linearly related to potato plant density across the field landscape each year (Fig. 2). The linear response of the data indicated that the stems per plant were not influenced by plant density. Plant density ranged from 2.0 to 4.5 plants m^{-2} across years and maximum stem density approached 26 and 16 stems m^{-2} during 2002 and 2003, respectively. Maximum stem density was higher in 2002 than in 2003 because stems per plant were 60% higher in 2002, hence the differences in response between years. In 2002 each plant had approximately 4.5 stems per plant and only 2.9 stems per plant in 2003.

Tuber density increased with plant and stem density across years (Fig. 3). Initial analysis showed that tuber density was slightly higher in 2002 than 2003, but on deeper investigation the differences in

tuber density were due to slightly higher stem densities in 2002 (Fig. 2). Nonlinear models did not describe data any better than linear regression (data not shown). However, tubers per plant decreased with increasing plant and stem density in 2002, suggesting that slope was not constant as was predicted by linear regression. Therefore, nonlinear models were used to describe response of tuber density to plant and stem density. A single nonlinear model was fit across both years because describing tuber density response independently each year did not explain any more of the data based on an *F* test (data not shown). In addition, parameter estimates were consistent across both years. Plant density described 27% of the variation in the tuber density data across both years. Tuber set was 30 tubers per plant in the absence of intraspecific competition (initial slope of the curve) and the maximum tuber set was 187 tubers m^{-2}. Stem density described 55% of the tuber density across years. Tuber set was 7.6 tubers per stem in the absence of intraspecific competition, and the maximum was estimated at 196 tubers m^{-2}.

Yield increased with plant, stem, and tuber density and was predicted with nonlinear models (Fig. 4). In predicting yield, nonlinear regression described more of the data based on plant, stem, and tuber density than linear regression based on lack-of-fit tests. Because yield was similar across years and parameter estimates did not differ, the data were combined for quantifying yield response to plant, stem, and tuber density. Plant density explained only 6% of the variability in yield, but the parameter estimates were highly significant ($P < 0.01$) with an estimated maximum yield of 82 Mg ha^{-1} and yield per plant at low densities of 88 Mg ha^{-1}. The estimate of yield per plant at low densities was significant ($P = 0.002$) but had a large error due to the lack of data collected at low densities. Stem density described 19% of the variability in the yield data, with each stem contributing 20 Mg ha^{-1} at low densities and a maximum estimated yield of 86 Mg ha^{-1}. Tuber density provided the greatest explanatory power, predicting 22% of the variation in yield. Potato yield was 2.7 Mg ha^{-1} per tuber at low densities, with maximum yield estimated at 100 Mg ha^{-1}.

Average tuber size decreased with increasing stem and tuber density (Fig. 5). Data were combined due to similar parameter values across years and lack of improved fit with individual analysis each year. Potato tubers were smaller in 2002 due to higher stem and tuber density compared to 2003. Inverse yield law described more of the data than linear regression in large part due to response at higher tuber densities in 2002. Stem density described 26% of the average tuber size variability with a maximum of 210 g $tuber^{-1}$. Tuber density described 26% of the variability in average tuber size as well, but the maximum was 245 g $tuber^{-1}$. Estimates of maximum tuber size were not different when describing the response to tuber versus stem density.

The potato tuber and stem density also appeared to affect the distribution of tuber size (Fig. 6a). Examples from plots selected from extreme tuber or stem densities were presented to illustrate the range in tuber size distributions. The most limiting property of the data was that tuber size was strictly positive, requiring a probability density with a strictly positive range, thus precluding the popular normal (Gaussian) density. In addition, the tuber

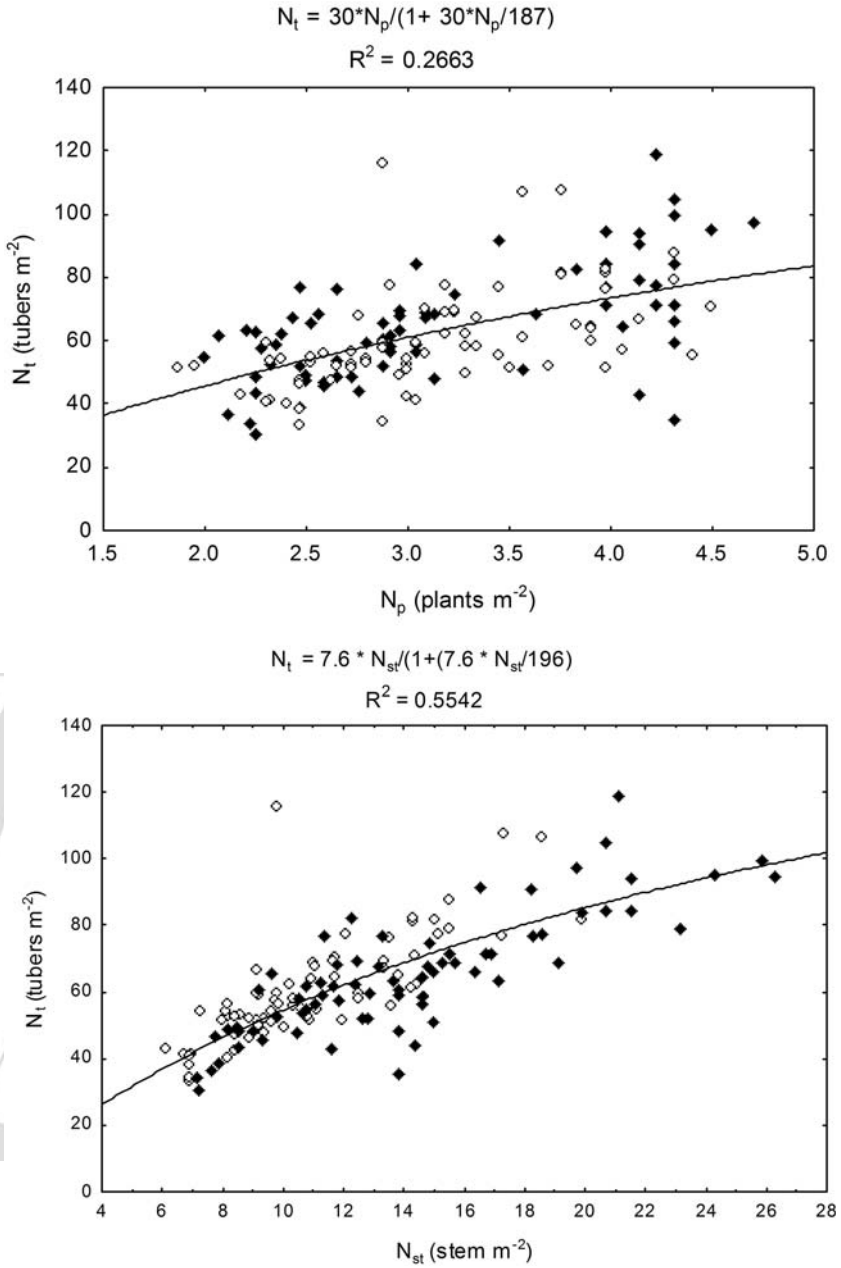

Figure 3. Potato tuber density response to plant and stem density in a commercial potato production field during 2002 and 2003 near Coloma, WI.

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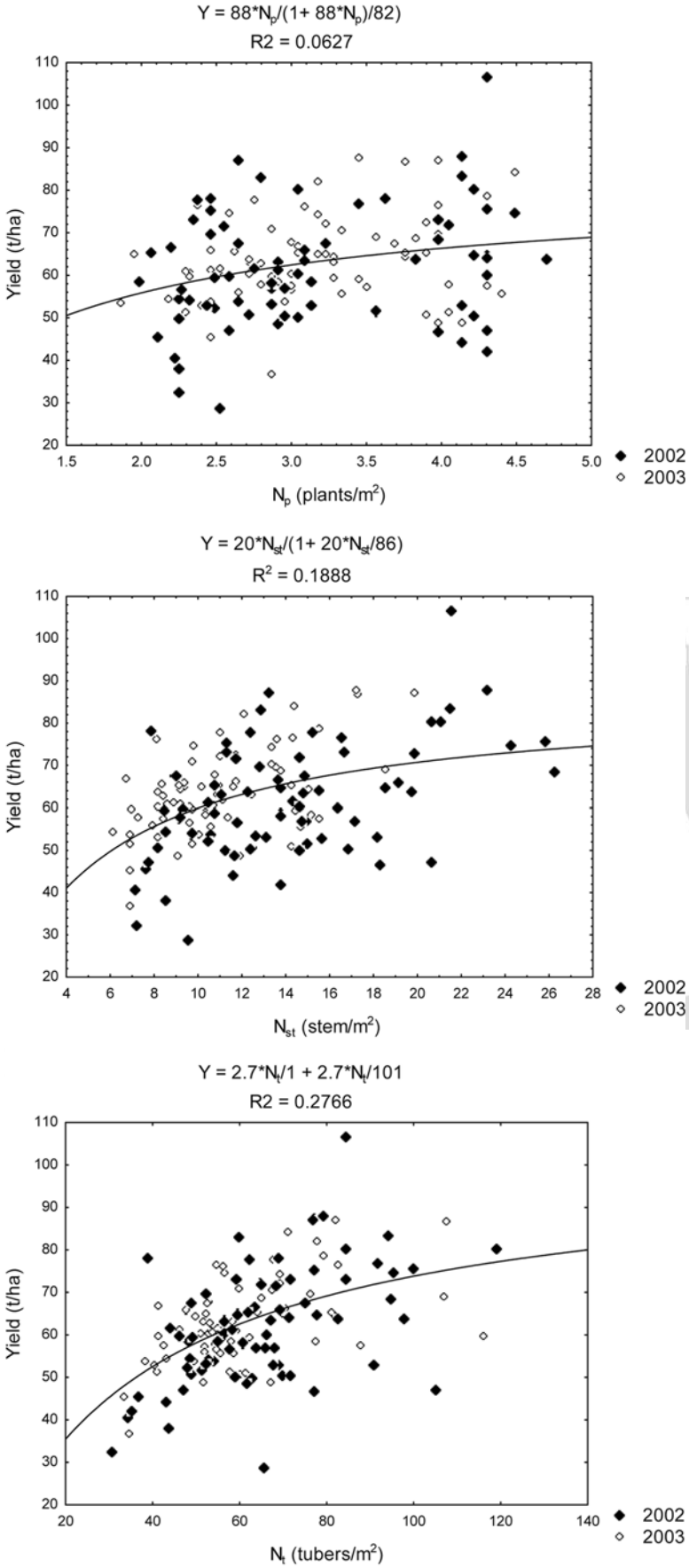

Figure 4. Relationship between potato yield and plant, stem, and tuber density in commercial field trials during 2002 and 2003 near Coloma, WI.

size distribution was skewed right or left, or symmetric for different plots, requiring a flexible probability density function able to capture these possible shapes. The Weibull distribution predicted the proportion of tubers falling into each size category and improved estimation relative to a normal distribution (data not presented). The Weibull distribution can be estimated using the data for an individual plot (Fig. 6b). However, statistical analysis (not shown) indicated that pooling the data across treatments and years was appropriate. In addition, the tuber size distribution and its response to changing stem or tuber densities were successfully estimated by directly estimating α and using Eq. [6] for β (Tables 1 and 2).

Using either the stem or tuber density provided R^2 values of 0.93 for fitting the cumulative proportion of tubers by size (Tables 1 and 2). The surface response of the cumulative proportion of tubers by size was presented across different stem densities (Fig. 7). The surface was similar across tuber densities (data not shown). The plotted surface was the cumulative proportion of tubers by size category as reported in Eq. [5], with constant value for α and the value for β calculated as a function of stem density N_{st} using Eq. [6] and the estimated β_0 and β_1 (Table 1).

Examination of the proportion of tubers by size as predicted by the probability density function (Fig. 8) seemed more intuitive, rather than the cumulative proportion of tubers by size category as predicted by the cumulative distribution function (Fig. 7). The implied tuber size distribution in Fig. 8 was conditional on stem density. The plotted surface was the tuber size distribution reported in Eq. [4], with constant value for α and β calculated as a function of stem density N_{st} using Eq. 6 and the estimated β_0 and β_1 (Table 1). As the stem density increased, the estimated tuber size distribution shifted so that the proportion of large tubers decreased and the proportion of small tubers increased. The estimated proportion of tubers around 150 g remained relatively constant across all stem densities, while the proportion of small tubers (generally <150 g) increased with the stem density and the proportion of large tubers (generally >150 g) decreased with stem density.

DISCUSSION

Variability in plant density in response to in-row spacing was high, but this may be attributable to the mechanical planting operation (Fig. 1). Previous research in potato has reported variation in plant density due to the efficacy of mechanical planting operations (Pavek and Thornton, 2005; Schotzko et al., 1984). Field corn (*Zea mays* L.) has seen similar variations in stand establishment across fields (Lauer

and Rankin, 2004). Small-plot research trials that were mechanically planted have seen similar variation in wheat (*Triticum aestivum* L.), sunflower (*Helianthus annuus* L.), and canola (*Brassica rapa* L.) stands due to variability in the operation of mechanical planting (Holman et al., 2004). Sampling error associated with the data collection method may also have contributed to variability in plant establishment in response to mechanical planting. Samples of five plants were collected from each subplot, which allowed for detailed measurements of stem, tuber, tuber size, and other parameters. This may have increased the error of true mean within each area of the field where the sample was collected. Each sample plot was 1 to 3 m of row, which is a common area assessment for determining crop status during the year. Variability in stand and other potato data may have been influence by sampling error, but the variation was within previously reported estimates in planting operation (Pavek and Thornton, 2005). This error did not influence various relationships or the interpretation of the data. Furthermore, the sample size permitted extensive sampling within the trial, allowing for ample data points to fit the different regression functions. Another source of error may have been the development of double drops. Double drops occur where more than one potato seed piece has been placed in a single hill and would have resulted in six instead of five plant samples in this research (Pavek and Thornton, 2005). Double drops were unavoidable but would have only adversely influenced relationships with plant density. Stem and tuber density responses should not have been affected by double drops other than to potentially increase stem and tuber densities. Finally, sample variation could have been influenced by spatial variability within the field. This experiment was conducted in a 16-ha field, and sample-to-sample variation may have affected results. However, many of the models were accurately predicted despite the spatial variability, further emphasizing their biological importance in determination of potato crop response.

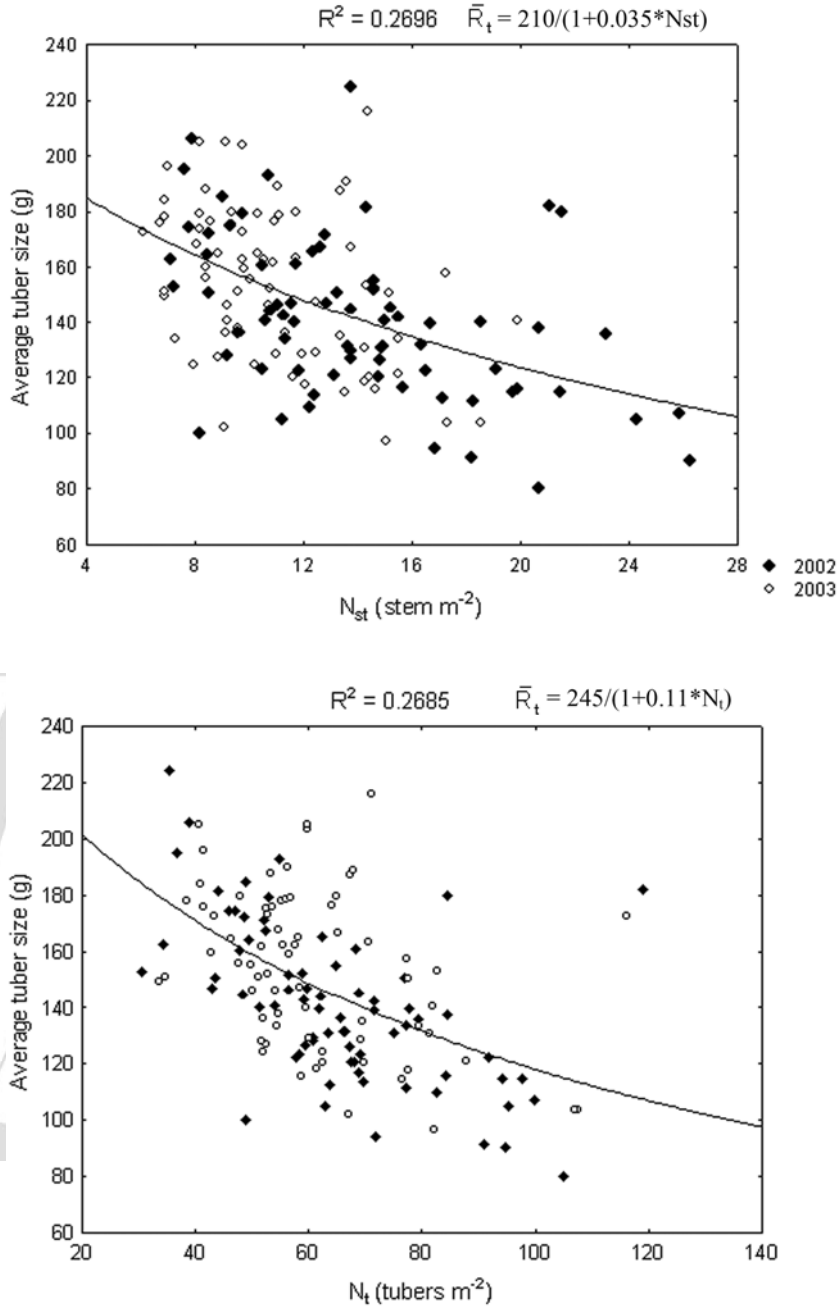

Figure 5. Average tuber size in response to stem and tuber density in commercial field trials during 2002 and 2003 near Coloma, WI.

Stems per plant was constant across the range of densities observed within these trials, resulting in a linear relationship between stem and plant densities (Fig. 2). Previous research has demonstrated that stem density is rarely influenced by intraspecific competition in potato (Allen and Wurr, 1992; Bleasdale, 1965; De la Morena et al., 1994; Iritani et al., 1983; Knowles and Knowles, 2006; Knowles et al., 1985; Love and Thompson-Johns, 1999; Lynch and Rowberry, 1977; O'Brien and Allen, 1992; Rex, 1991; Strange and Blackmore, 1990; Wurr et al., 1990, 1992, 1993). Year-to-year variability in stem set per plant (slopes from linear models in Fig. 2) occurred, leading to different relationships between stems per meter and plant density. Recent research has illustrated the influence of seed tuber size, physiological age, and handling on the stem set of potato seed of the same cultivar (Iritani et al., 1983; Knowles and Knowles, 2006; Knowles et al., 1985; O'Brien and Allen, 1992). The seed was from different sources and produced under different growing conditions during 2002 and 2003, likely resulting in different response across years. In addition, many experiments

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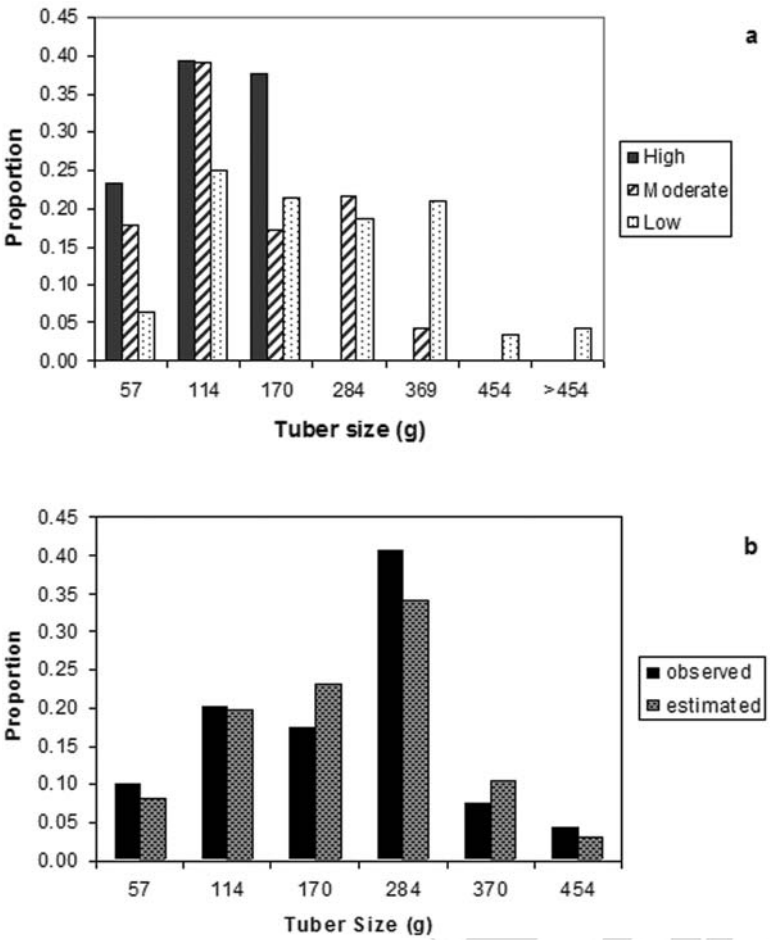

Figure 6. (a) Proportion of tubers fitting into each size category from three plots selected with high, medium, and low density, and (b) observed versus estimated proportion of tubers within each size category for a select plot from commercial field trials near Coloma, WI.

evaluating the influence of seed on stem set commonly used seed tubers from common size categories, but commercial seed was used in this study that included whole seed as well as cut seed from tubers 70 to 280 g. Even though 90% of seed pieces were 65 to 75 g (data not shown), the current research suggests the seed could produce variable stem per plant if derived from different-sized seed tubers. Allen and Wurr (1992) suggested that stem density should be assessed during early plant development, around the time of tuber initiation. New stems seldom initiate after tuber set, and few have senesced that early in the growing season. Stems were counted at harvest in this trial to allow for destructive harvest due to the propensity of potato to branch under ground. Accuracy of stem counts may have been compromised to allow for destructive sampling at harvest, but this was the only way to avoid sampling error in the determination of stem density.

Tuber per plant decreased with increasing plant and stem densities observed within these trials, resulting in nonlinear relationship between tuber set and density (Fig. 3). Interspecific competition has been observed in other research to reduce tubers per plant as potato density increased (Allen and Wurr, 1992; Bleasdale, 1965; De la Morena et al., 1994; Iritani et al., 1983; Knowles and Knowles, 2006; Knowles et al., 1985; Love and Thompson-Johns, 1999; Lynch and Rowberry, 1977; Lynch et al., 2001; O'Brien and Allen, 1992; Rex, 1991; Strange and Blackmore, 1990; Wurr et al., 1990, 1992, 1993). The hyperbolic model (Eq. [1]) accurately predicted tuber density in response to plant and stem density. Somewhat surprising was that the response in tuber density to stem density was similar across the 2 yr of the study and that stem density explained more than 50% of the variation in tuber density. This occurred despite potential differences across years, seed, and spatial variability over the field landscape. Tuber set per stem has been shown to be highly conserved across years in previous experiments, but under tightly controlled conditions (Knowles and Knowles, 2006; Knowles et al., 1985; Love and Thompson-Johns, 1999; O'Brien and Allen, 1992). In contrast, Lynch et al. (2001) reported variable tuber per stem affected by factors independent of plant density. This research indicated that the relationship between stem and tuber density held true in field-scale production. One item to note was that maximum tuber density within this trial was measured to be 120 tubers m^{-2} and estimated at 180 tubers m^{-2}. The measured tuber density for Russet Burbank was three times as high as reported in research from the western United States (Love and Thompson-Johns, 1999). Discrepancies in tuber set per stem by common varieties across different growing regions may require specific seed management and crop planting rates to optimize tuber densities within each region.

Yield increased with potato crop density, and the response to plant, stem, and tuber density was described with nonlinear relationship (Fig. 4). Yield response to crop

Table 1. Least squares estimated parameters for the Weibull distribution describing the distribution of potato tuber sizes as a function of tuber density.

Parameter†	Estimate	SE	*t* statistic	*p* value
β_0	5.515	0.02968	185.9	<0.001
β_1	−0.007192	0.0004581	−15.70	<0.001
α	1.817	0.03682	49.36	<0.001

†Parameter estimates derived from Eq. [4], [5], and [6] with R^2 = 0.930.

Table 2. Least squares estimated parameters for the Weibull distribution describing the distribution of potato tuber sizes as a function of stem density.

Parameter†	Estimate	SE	*t* statistic	*p* value
β_0	5.434	0.02435	223.1	<0.001
β_1	−0.02963	0.001856	−15.96	<0.001
α	1.826	0.03672	49.71	<0.001

†Parameter estimates derived from Eq. [4], [5], and [6] with R^2 = 0.931.

density was not surprising as several other researchers have documented similar relationships to potato density (Allen and Wurr, 1992; Bleasdale, 1965; De la Morena et al., 1994; Iritani et al., 1983; Lynch et al., 2001; Knowles and Knowles, 2006; Knowles et al., 1985; Love and Thompson-Johns, 1999; Lynch and Rowberry, 1977; O'Brien and Allen, 1992; Rex, 1991; Strange and Blackmore, 1990; Wurr et al., 1990, 1992, 1993). De la Morena (1994) identified stem density as the most relevant predictor of potato crop yield through path analysis. Other researchers have agreed that stem density was the most appropriate measure of plant density for predicting potato yield (Allen and Wurr, 1992; Bleasdale, 1965; Iritani et al., 1983; Love and Thompson-Johns, 1999; Wurr et al., 1990, 1992, 1993). Our data agrees in that stem density explained much more of the variability in yield than did plant density in large part due to variability in stem density per plant. Stem density described nearly 20% of the data across years, landscape, and seed. Tuber density described slightly more of the variation in yield, but managing tuber density poses more challenges than stems because it is not easily quantified on field inspection. In addition, stem density explained slightly more than half of the variability in tuber density.

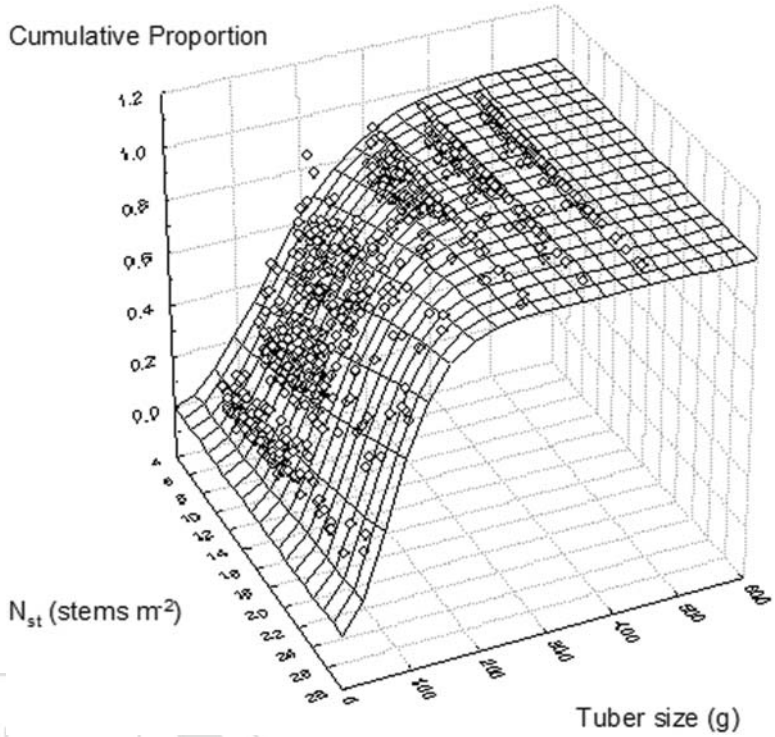

Figure 7. Observed and estimated cumulative proportion of potato tubers with increasing tuber size across different stem densities in commercial field trials near Coloma, WI, across 2002 and 2003. Individual data points were provided (O) to illustrate fit of the predicted response.

The hyperbolic model (Eq. [2]) used to predict tuber set and yield has not been previously used to predict potato yield response to crop density (Fig. 4). The model was successfully fit to yield data across different density measurements and described more of the variability in yield than linear regression. The primary benefit of the hyperbolic model was the fitting of biologically significant parameter estimates, per plant yield at low density and maximum yield or yield potential (Cousens et al., 1987; Holman et al., 2004; Jasieniuk et al., 2001). Quadratic or square root models included parameter estimates with minimal biological meaning, especially if nonzero intercepts were fit (Allen and Wurr, 1992; Lynch et al., 2001; Knowles and Knowles, 2006; Wurr et al., 1990, 1992, 1993). The relative ability of different models to accurately predict data can be debated, but the hyperbolic model required fitting of only two parameter estimates compared with three for quadratic or square root models (Cousens et al., 1987). A weakness of the hyperbolic model was that it will not fit decline in crop yield at extremely high crop densities, but that has rarely been observed in data of potato yield (Knowles and Knowles, 2006; Knowles et al., 1985; Love and Thompson-Johns, 1999; Lynch and Rowberry, 1977; O'Brien and Allen, 1992; Rex, 1991; Strange and Blackmore, 1990; Wurr et al., 1990, 1992, 1993). The challenge of fitting the hyperbolic model was the need for data at the density extremes, both low and high. Estimates of *i* and *a* were equal when predicting potato yield response to plant density, and *i* may have been overestimated when predicting yield response to tuber and stem density due to lack of data at low densities. Similarly, maximum tuber density (Fig. 3) was likely overestimated, due to lack of high enough densities to determine tuber response at the

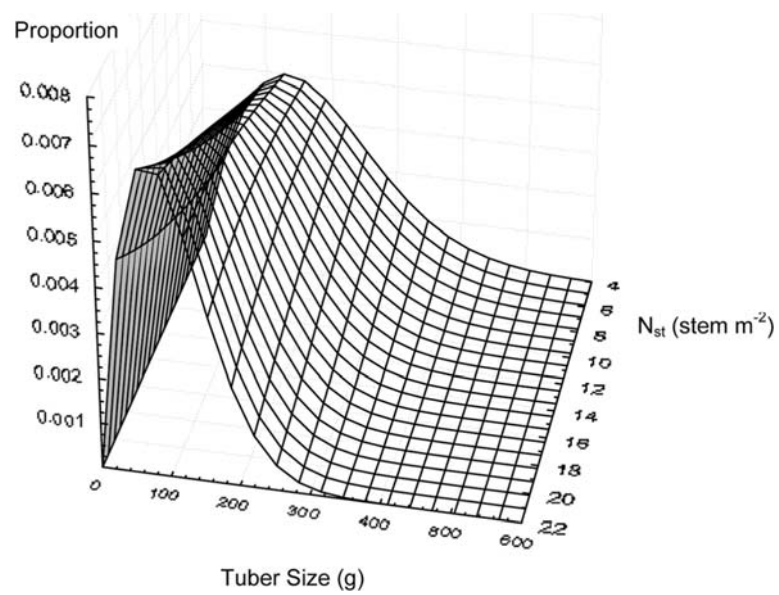

Figure 8. Estimated tuber size distribution across different stem densities estimated with data from commercial field trials from 2002 and 2003 near Coloma, WI.

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extremes. However, the model explained tuber set and yield response to potato density within the range of data collected, and parameter estimates were determined that were different than zero. Most statistical software can easily complete nonlinear regression analysis, and the hyperbolic estimation of yield response to density seems suitable, especially for potato where negative yield response at extremely high densities has not been observed.

Average tuber size decreased with increasing stem or tuber density (Fig. 5). Plant density was not used to estimate tuber size because of variability seen in the estimation of crop yield, suggested plant and tuber densities were more suitable management factors. The modified inverse yield law (Eq. [3]) was used to predict the change in average tuber size with increasing plant density (Holliday, 1960; Weiner, 1982). Potato yield per plant was predicted with different versions of the inverse yield law (Lynch and Rowberry, 1977), but it has not been used to describe changes in tuber size in response to increasing density. Average tuber size has been predicted with square root models or polynomial regression (Allen and Wurr, 1992; Wurr et al., 1992). As discussed earlier, this leads to the development of parameter estimates with little biological meaning and requires the fitting of three parameter models in the case of square root and quadratic functions compared with two parameters for the inverse yield model. The inverse yield law predicted theoretical maximum size unit, in this case, maximum average tuber size. The inverse yield law accurately estimated the response in average tuber size to increasing stem and plant density across years and over the field landscape. Stem and tuber density were similar in the proportion of the variability of the data that they described, providing further evidence in support of using stem rather than tuber density as the unit of management due to ease in counting stems relative to tubers (Allen and Wurr, 1992). The inverse yield law requires a broad range of densities for accurate parameter estimation, especially R_{max}, similar to fitting the hyperbolic yield model above (Weiner, 1982).

Potato and other vegetable crops are commonly priced differently across a range of product sizes (tubers in the case of potato). Predicting average tuber size alone does not provide enough information on the distribution of tuber sizes to predict crop value. Tuber size data have commonly been reported across six or more categories independently (Arsenault et al., 2001; Love and Thompson-Johns, 1999; Zebarth et al., 2006). However, this has limited utility in quantifying the response of tuber size over a continuous variable such as crop density or for estimating the proportion of tubers that are of a size not directly measured. To address this issue, average tuber size and the tuber size distribution has been estimated with a normal distribution that allowed for evaluation of management factors on each size category (Travis, 1987; Wurr et al., 1992). Average tuber size and spread were influenced by management, including reductions in both as stem density increased. However, this approach had limited utility in potato because average tuber size did not always have a normal distribution (Love and Thompson-Johns, 1999; Zebarth et al., 2006). A Weibull distribution with three parameters effectively predicted the cumulative distribution function of potato tuber size across a range of stem and tuber densities, years, and the field landscape (Tables 1 and 2). The estimated cumulative distribution function allowed for prediction of the proportion of tubers in any size category across the range of densities evaluated within this trial (Fig. 7). Furthermore, the associated probability density function estimated the change in the proportion of tubers by size as a continuous function of tuber size (Fig. 8). The modeling of potato yield and the tuber size distribution will facilitate improved economic evaluations of potato management practices and crop value. Future research will focus on refining estimation of the tuber size distribution as well as using the model to predict crop value and economic return in response to management. Sensitivity analysis will allow the identification of variables most important for maximizing the profitability of potato production.

This research illustrates the utility of several nonlinear models for explaining potato yield response to increasing crop density. The hyperbolic model and inverse yield model provided biologically meaningful parameter estimates that will provide new insights in the optimization of potato crop productivity. Acceptable commercial crop yield of 55 t ha^{-1} was achieved with minimum densities of eight stems and 50 tubers m^{-2}. Doubling crop density only increased predicted yield by 7 t ha^{-1} but reduced average tuber size by 20% and increased the proportion of undersized tubers by 10%. In addition, these models should provide insights into understanding the influence of other crop management practices on potato. For example, documenting the influence of weed interference on potato productivity should focus on tuber set per plant, tuber size, and tuber size distribution to understand yield responses to interspecific competition. Furthermore, the prediction of tuber size distribution will allow for economic assessments of crop value that were previously limited.

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