Effects of Harvest Date and Storage Duration on End-Product Quality of Three Processing Potato Varieties

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AUTHORIZATION TO SUBMIT DISSERTATION

This dissertation of Addie M. Waxman, submitted for the degree of Doctor of Philosophy with a major in Plant Sciences and titled "EFFECTS OF HARVEST DATE AND STORAGE DURATION ON END-PRODUCT QUALITY OF THREE PROCESSING POTATO VARIETIES," has been reviewed in final form. Permission, as indicated by the signatures and dates given below, is now granted to submit final copies to the College of Graduate Studies for approval.

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ABSTRACT

Texture quality of French fries is an important characteristic for customer satisfaction. Determining the effects plant maturity and harvest timing on specific textural quality characteristics of French fries during raw potato (*Solanum tuberosum* L.) storage are needed. A two year study evaluated the effects of three harvest dates; early (prior to physiological maturity), normal (at physiological maturity), and late (after physiological maturity), on quality attributes of French fries produced from processing tubers of three varieties, Russet Burbank, Clearwater Russet, and Alpine Russet over a nine month storage season at 8.3^{o}C. Analysis of specific textural attributes was evaluated, including crispness, external shell, mealiness, moistness, texture variation, texture defects, and internal appearance. Fry color, glucose and sucrose concentrations, and sprout development were analyzed over the nine month storage season. Yield data were evaluated using a mock contract to ascertain the economic impact of harvest timing on gross return for three varieties. Early harvest produced lower total yields and negatively affected growers' adjusted price with losses due primarily to low specific gravities. Early harvest incentives with Russet Burbank were insufficient to compensate growers for harvesting early. French fry texture quality from harvest through the nine month storage season was negatively impacted by an early harvest, especially with regard to crispness. Late harvest produced higher total yield/ha of tubers >170 grams, thereby increasing adjusted price. Clearwater Russet produced higher yields of undersized tubers when harvested early. Clearwater Russet had high specific gravities that increased the adjusted price and maintained good textural quality and fry color quality throughout the storage season. Alpine Russet experienced moderate to severe declines in textural quality and fry color quality over the storage season. Russet Burbank produced high total yields, however, it produced tubers with low specific gravity, and significantly reducing the adjusted price. Russet Burbank experienced significant declines in textural quality and fry color quality over the storage season. Overall, early harvest was detrimental to total yield, textural end-product quality and base prices of all varieties, although Clearwater Russet maintained desirable texture and fry quality throughout a nine month storage season.

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DEDICATION

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INTRODUCTION

It is well documented that harvesting potatoes as close as possible to physiological maturity will produce higher quality potatoes for processing and, in turn, provide higher quality end-product (Driskill *et al*. 2007, Stark & Love, 2003 and Knowles *et al.*, 2009). Potato crops harvested at physiological maturity tend to produce high quality end-products, as well as store with reduced incidence of disease and sprouting in long-term storage conditions (Bethke & Busse, 2010). Physiological maturity is defined as the number of days after planting in which the potato crop has achieved as close as possible maximum yield, maximum specific gravity, minimum reducing sugars, and minimum sucrose (Wohleb, *et al.,* 2010). Physiological maturity can also be determined via signs of physical maturity, such as senescence of plants and degree of skin set (Narasimhamoorthy, 2013). The choice of variety also plays a major role when determining maturity as each variety has its own timing of senescence (Dehdar *et al.,* 2012). The length of the growing season and planting, growing, and harvest conditions are key points to consider when assessing physiological maturity (Mackerron & Davies, 1986).

Harvest timing decisions are often based on criteria other than physiological maturity. Grower contracts and processor requests often require harvesting outside of physiological maturity parameters in an attempt to supply the processing plants with new crop potatoes, as opposed to processing with older potatoes that have been held for months in long-term storage (Curtis, 2003). In addition, weather conditions often prohibit harvesting at optimal physiological maturity and the crop is harvested later than preferred. Deviation from harvesting at physiological maturity, whether earlier or later than recommended, can negatively impact end-product quality (Stark & Love, 2003).

With regard to French fry processing, end-product quality is defined by an assortment of traits that quantify flavor, color, taste and texture of edible potato products (FDA, 2011). However, in potato processing, this single and seemingly simple term is actually the driving force behind a vast array of objective and subjective quality measures, tests, and controls devised to ensure that processors deliver a consistent and marketable product.

CHAIN OF POTATO PRODUCTION

Potato production chain begins first with creating and signing of a contract. This legally binding contract between a grower and processor states the specific parameters the grower must meet in order to sell his crop (Curtis, 2003). A base price per metric ton of potatoes is set by the buyer (Bolotova et al., 2010) through collective bargaining with growers. The crop is then planted, grown, and harvested. If the crop meets the basic requirements, the sale is finalized and the crop is sold to the buyer or processor (Rossell, 2001). The processor takes the purchased crop of potatoes and processes into a variety of products for the next customers, the retailers and foodservice operators. The processed material must meet buyer standards in terms of color, size, taste, texture, aroma, and overall appearance (Penson & Capps, 2014). The retailer then sells the processed items to the final end-use customer (Taylor *et al.,* 2007).

The contract sets the price for the raw product which then influences the potential price and profit of the final product (Somsen & Capelle, 2004). Furthermore, when evaluating potential new varieties, growers want to know the impact that variety will have upon their net price as stated within the grower contract. The contract not only states base price incentives and penalties, but is oftentimes the standard by which a grower will ascertain economic value of new varieties (Somsen & Capelle, 2002).

Parameters specific to potato quality are outlined within the processing contracts, including specific gravity, fry color, incidence of the physiological disorder sugar ends, percent bruise-free, percent of #2's, % of rocks, % of tubers greater than 6 ounces, and % of corn debris (Bolotova, *et al., 2010)*. Potatoes must meet basic quality standards for purchase by the buyer. In addition, the purchase price can be adjusted based upon a sliding scale that is specified in the contract (Curtis, 2003). This allows for increases in price if quality parameters exceed contract specifications, thresholds or decreases in price if quality parameters are below specifications (Wilson, 1986).

Growers who have signed contracts with processors have assurances of a reliable buyer with a set base price for their potatoes at harvest (Eaton, *et al.,* 2001). Growers can also take advantage of technology and skilled assistance provided by the buyer or contacts of the buyer that the grower may not have been able to afford without their contract association (Curtis, 2003). Having a signed contract can also provide the grower with access to credit that would have been previously denied (Curtis, 2003).

Once the potatoes have been purchased, the processing company can either process the potatoes immediately or place them into storage. Potatoes are processed into end-products year-round in order to meet the high demand of the end-use customer. Therefore, potatoes must be available throughout the year for production and this is achieved by placing the potatoes into short to long-term storage (Guenthner, 1995).

Potatoes are then processed into a variety of end-products, each of them meeting the quality standards of the third link in the potato production chain, the retail restaurants, food stores, and food service establishments (Rossell, 2001). The third link of the chain includes retail quick service restaurants (QSR's), grocery stores, and food service establishments, such as school systems, hospitals, and the military (Sterns *et al., 1994*). All of these institutions sell their products to the final link of the potato production chain, the consumer. Retail outlets and food service establishments prepare the final product in-house and sell to the consumer for immediate and oftentimes, on-site consumption (Sterns *et al., 1994)*. Grocery stores also sell frozen, dried, or canned end-products for preparation in off-site locations, primarily in the home (Taylor *et al.*, 2007). Quick service restaurants, dining restaurants, and grocery store chains are the only link in the chain with face to face contact with the consumer. These establishments have the daily challenge of meeting the demanding and unpredictable standards of the general public. (Taylor *et al.*, 2007).

DESIRED TRAITS OF PROCESSING POTATOES

Not all potato varieties possess the desired characteristics that render them capable of meeting processing industry standards. Numerous traits, ranging from agronomic performance to processing quality, all play a role in a variety's acceptance by growers, processors and end-use customers.

High yield, approximately 60 t/ha to 80 t/ha, is a basic requirement of a processing variety (USDA.gov, 2014). Potato processors used over 14 million metric tons to produce French fries, chips, dehydrated products, and canned goods in 2012 (Bosse & Boland, 2014). Of that number, 8.5 million metric tons were used to make par-fried potato products, i.e. potatoes products which are partially fried in the production plant and require a final cooking step at the retail store or home. This includes the basic French fry and extruded potato products. (Bosse & Boland, 2014). Therefore, to meet demand, a potato variety must be capable of producing large volumes of high-quality raw product.

Producing a high yield, by itself, is not enough to meet the specifications of processors. Growers must also strive to produce potatoes that possess a high percentage of U.S. No. 1 potatoes. The USDA standards for U.S. No. 1 potatoes state that they must be firm, fairly clean, possess good shape per their variety, free from certain diseases, and possess a certain size as designated by the variety and market class. (USDA AMS, 2013). Most contracts between farmers and processors specifically define the percentage of U.S. No. 1 potatoes required to be in compliance with the contract (Curtis, 2003).

Meeting basic size and shape requirements is crucial for farmers contracted with French fry processors (Si, *et al.,* 2016). In order to meet the longer length of French fries so desired by consumers, potato size of >170 grams is a stated parameter within the contract (Curtis, 2003). Potatoes destined for French fry processing should have the desired length to width ratio. Potatoes that are oval or ellipsoidal in shape with a higher length to width ratio, 1.6 to 2.0, will tend to produce longer French fries with less waste than round potatoes with a lower length to wide ratio (1.0 to 1.4) (Si *et al.,* 2016 and Tabatabaeefar, 2002).

Specific gravity, a ratio of starch to water or tuber density, is the primary industry standard measurement of potato quality. Potatoes with a high specific gravity tend to produce higher quality French fries than potatoes with low specific gravity (Driskill *et al.,* 2007). Numerous research studies have detailed the high correlation between raw potatoes with high starch content and several highly desirable traits of French fries, such as crispness, mealiness, and moisture content. (Clark *et al.,* 1940; Kleinschmidt *et al.*, 1984; Sabba *et al.,* 2007; Singh & Kaur, 2009) Specific gravity differs widely among varieties, but it also can be affected by environmental and cultural factors such as nutrient management, heat stress, and water stress (Kissmeyer-Nielsen & Weckel, 1967). Furthermore, specific gravity is indicative of tuber quality to such an extent, that most potato contracts have specific gravity standards that influence the overall value of the crop (Curtis, 2003).

Specific gravity is an approximation of the amount of dry matter and thus starch within a potato and is based upon composition of the potato sample (Liu *et al.,* 2003). Potato composition is variety dependent, but generally comprised of water, total tuber solids, protein, and fat. Total tuber solids are further broken down into starch, sugars, non-starch polysaccharides, and phenolic compounds. Of the total tuber solids, 65% to 80% of the dry weight of a tuber is starch (Singh & Kaur, 2009).

Specific gravity can be easily calculated by using a universally accepted method called the ‘weight in air/weight in water’ method (Kleinschmidt *et al*., 1984). A clean and dry sample of potatoes is weighed in the air, then submerged in water and weighed under water. Those numbers are entered into the following equation:

Specific gravity = Weight in air / (Weight in air – weight in water)

The number generated is standardly used within the processing industry as an indicator of starch content, which is a further indicator of end-product quality (Stark & Love, 2003).

Another criterion for determining if a variety is fit to be a processing variety is the variety’s ability to store throughout the storage season with minimal disease pressure. Of particular concern for long term storage is resistance to common storage diseases, such as Fusarium dry rot, Pythium leak and soft rot. A good processing variety will possess adequate resistance to pathogens, both fungal and bacterial, while maintaining a high state of quality over time (Secor & Gudmestad, 1999).

Evaluating the dormancy characteristics of a potential variety is also essential to meeting consumer demand for processed potato products. Dormancy is the natural length of time that a potato can be stored before sprouting occurs (Sorce, *et al.,* 2005). Sprouting in storage can be a quality issue because it signals the conversion of the valuable starch within the potato into reducing sugars that can create undesirably darkened French fries (Nourian *et al.,* 2003). Sprouting can also cause significant tuber weight loss, resulting in economic losses due to less saleable product. (Nourian *et al.,* 2003). Storage dormancy can be prolonged with the application of sprout inhibiting chemicals, such as chlorpropham or methylnaphthalenes, however, using a variety that displays a longer natural dormancy will help reduce the need for using sprout inhibitors during extended storage periods (Sorce, *et al.,* 2005).

The physiological disorder known as "sugar ends" is typically caused by stressful field conditions that interrupt the conversion of sucrose to starch, thereby causing sucrose to accumulate in the stem end of the potato (Kleinkopf*, et al.,* 1992). High soil temperatures and insufficient soil moisture levels, particularly during early tuber bulking, promote the development of sugar ends (Zommick *et al.,* 2014). Excessively low or high nitrogen levels can also exacerbate sugar end development (Thompson *et al*., 2008). Sucrose, although itself not a reducing sugar, is hydrolyzed by the enzyme acid invertase to form the reducing sugars, glucose and fructose (Thompson, *et al.,* 2008). When potatoes are exposed to high temperatures during frying, a non-enzymatic Maillard reaction occurs, which is a chemical reaction between reducing sugars, glucose and fructose, and free amino acids within the potato cell (Fennema, 1996). The result is darkening of the French fry on the stem end, which is negatively perceived by the end-use customer. Textural issues and a decline in taste and flavor quality have also been noted with chips and fries made from tubers with high stem end sugar contents (Noda *et al*., 2004). Therefore, good processing varieties should possess relatively low sucrose, which reduces the amount of substrate available for hydrolysis to reducing sugars and overall low reducing sugar concentrations, decreasing the available reducing sugars needed for the non-enzymatic Maillard reaction.

Many varieties of potatoes are susceptible to cold temperature sweetening (CTS), which is the conversion of sucrose to glucose and fructose at an accelerated rate when stored at approximately 2 to 4^{o}C (Sowokinos, 2001). Potatoes with CTS tend to fry darker due to the non-enzymatic Maillard reaction that occurs when the subsequent reducing sugars react with free amino acids at high frying temperatures. The resistance to cold temperature sweetening, i.e. is the ability of the potato to resist the formation and accumulation of reducing sugars at low temperatures during storage, is a highly desirable trait (Sowokinos, 2001). Such resistance to CTS would allow potatoes to be stored long-term at lower temperatures without developing elevated levels of reducing sugars associated with the negative attribute of fry color darkening (Sowokinos, 2001). Furthermore, storing potatoes at low temperatures could also reduce the amount and number of sprout inhibitors needed for long term storage, thus reducing overall storage costs for the grower and processor (Novy, 2010).

Processors must also be aware of another sweetening disorder called senescent sweetening. This physiological condition is highly dependent upon variety with short-term dormancy varieties exhibiting a higher incidence of senescent sweetening (Groves *et al.,* 2005). The condition occurs when potatoes have been stored for a period of time at moderate to higher storage temperatures of 6 to 8^{o}C. Burton specifically noted that potatoes experienced senescence sweetening after 5 to 6 months at 10^{o}C (Burton, 1989). As the potatoes begin to experience cellular decline with membrane degradation over time, enzymes gain access to intracellular starch granules comprising of densely packed glucose chains (Smith *et al.,* 2005). The complex breakdown of the starch granule contributes to sugar accumulation (Smith *et al, 2005.*). The available sugars react with other amino acids within the cell during frying to form undesirable darkening of French fries. Groves *et al.* noted that maturity at harvest played a role with senescent sweetening in that overly mature tubers exhibited a more rapid formation of senescent sweetening (Groves *et al.,* 2005).

A French fry processing variety should also possess a resistance to mottling. Unlike the sugar end disorder in which the discoloration is concentrated on the stem end of the French fry, mottling occurs throughout the French fry as a thin, thread-like discoloration. This is regarded as a color quality defect and is undesirable in finished French fry product (Jankowski, 1997).

HARVEST TIMING

Under normal growing conditions, potato crops are planted, grown, and harvested using best management practices designed to produce a crop with good yields and high quality (Stark & Love, 2003). Harvest is normally timed as close to physiological maturity as possible to optimize tuber quality (Bethke & Busse, 2010). Harvest timing and maturity also include the evaluation of potato plant senescence, tuber size, and skin set (Lulai, 2002; Mackerron & Davies, 1986).

Physiological maturity is defined as the number of days after planting when the potato crop has achieved maximum yield, maximum specific gravity, minimum reducing sugars, and minimum sucrose (Wohleb *et al.,* 2010). Harvesting at or near physiological maturity provides the potato crop with the necessary number of growing days in the field for sucrose production via photosynthesis to occur. The sucrose is eventually converted into starch and stored in the developing tubers. (Wohleb *et al.,* 2010). Deviating from the point of physiological maturity impacts the crucial characteristics that processors use as standards for assessing incoming product (Groves *et al*., 2005). Crops that are harvested early tend to have lower yield, smaller potatoes, lower specific gravity, and higher sugars due to a reduced number of growing days in the field (Narasimhamoorthy, 2013). Less time in the field decreases the total photosynthetic activity of the potato plant, which decreases the aggregate amount of sucrose that is produced. This reduces the available sucrose to be converted into starch as well as interferes with the sucrose to starch conversion process (Wohleb *et al.,* 2010). The reduction in starch synthesis results in less tuber bulking and smaller potatoes with lower specific gravities. The interference of the sucrose to starch process can lead to potatoes with higher sucrose levels as the sucrose remains intact within the tuber as opposed to being converted into starch (Geigenberger, 2003). Crops harvested past physiological maturity tend to have higher yield due to an increased tuber bulking period. The additional time in the field allows for further sucrose production, the conversion of sucrose to starch and subsequent starch storage within the tuber and an increase in tuber size. (Bethke & Busse, 2010). Reducing sugars and sucrose also start to increase over time as harvest is delayed This is due to the reversible nature of tuber storage in that starch can be converted back to sucrose when the tuber requires sucrose for respiration or as a reaction to stress (Geigenberger, 2003). Delaying harvest can increase the incidence of stress with additional temperature extremes and pest and disease pressure later in the season. Prior to tuber maturity, the action of the sucrose hydrolyzing enzyme, acid invertase, is inhibited by an invertase inhibitor protein, but as the potato ages, the levels of the inhibitor protein decline. The acid invertase hydrolyzes the newly available sucrose into glucose and fructose, which can potentially reduce French fry texture quality and produce fries with an undesirable darkened color (Iritani & Weller, 1980).

Advantages of Early Harvest

For processors, early harvest has its advantages. Potatoes harvested earlier in the season tend to produce higher quality French fries and potato chips than those that have exceeded physiological maturity in the field or have been stored for an extended period of time from the previous growing season (Mazza *et al.,* 1983). For growers, early harvested potatoes may bring higher prices in contracts and in the open market during a time when potatoes can be scarce.

Production costs can also be lowered by using early harvest potatoes (Gould, 1999). The use of these potatoes increases the rate of slicer efficiency in the production plants since their firmer composition allows for a cleaner slicing action (Somsen & Capelle, 2002). This more precise action increases the speed of the processing operation, reducing production time, and increasing output (Somsen & Capelle, 2002). A cleaner cut of the potato also reduces "feathering", which is a visual quality defect in French fries (Rossell, 2001).

Early harvested potatoes are easier and faster to peel than potatoes that have a more established, older peel (Gould, 1999). In order to peel potatoes to an acceptable level, tubers harvested at normal periods have a peel loss of 4% to 6%. This number increases with time in storage as the periderm matures. Older, stored potatoes have a peel loss of 6% to 8%. This is in marked contrast to freshly dug, new potatoes, which have only a 0.5% to 3% peel loss (Labs, 2003). With less time required in the abrasion and peeling machines, production time is optimized and profits are enhanced (Somsen & Capelle, 2002).

A reduction in peel loss further increases profits by providing an increase in the usable surface area of potato material available for producing the final product. This results in a reduction in raw potato costs over time (Somsen & Capelle, 2002). According to a recent economic study conducted at Utz Potato Chip Company, the savings in using early potatoes for a potato chip manufacturing plant can be approximately $32,000 per year. This number was based upon a $0.09 procurement cost, 8 hour per day production time, 5 days per week, 50 weeks per year (Labs, 2003). Cost minimization models generated for Frito-Lay also demonstrate the importance of reducing peel and trim loss by using early harvested potatoes. Their studies show a significant cost savings in using early harvested potatoes versus using potatoes dug at later intervals. (J. Guenthner, personal communication, 2014)

Harvesting early provides the growers with slightly more time in the fall to prepare the fields for the next season. Fall bedding, field maintenance, planting cover crops, and fertilizer can be applied with less worry about timing of winter conditions (Stark & Love, 2003). In addition, an early harvest provides more time for existing equipment to be utilized on more acres, thus spreading out overall equipment costs (Painter, 2011).

Growers can also utilize early harvest to reduce the impact of nematode damage. An early potato harvest reduces additional nematode reproduction and continued build-up within the field. Early harvest also reduces nematode blemish on potatoes and reduces the physical damage of the tubers caused by late generations of nematodes (Jaffee, 1992). An early harvest of potatoes can also reduce the potential occurrence of late blight by reducing the amount of time the potatoes are exposed to the pathogen in the field (Pacilly *et al.,* 2016).

Disadvantages of Early Harvest

Early harvest also has its own set of disadvantages for both the grower and the processors. Potatoes harvested at an earlier time can fail to meet the size requirements of the processors, particularly of French fry processors (Stark & Love, 2003). Although variety dependent, overall yield is lower with an early harvest when compared to later harvest dates (Burke, 2005; Waterer, 2007). Studies conducted by Narasimhamoorthy (2013) indicated that yield decreased by 60 to 85% when compared to harvests that were two and four weeks later (Narasimhamoorthy *et al.,* 2013). This reduction in total yield considerably reduces profits for the farmers who are paid by the weight of their crop (Eaton *et al.,* 2001). In addition, Narasimhamoorthy noted there was a reduction in tuber size with both of the study varieties with an early harvest, which reduced the number of marketable > 170g tubers by 14 to 67%. (Narasimhamoorthy *et al.,* 2013). This would indicate that the size parameters stated within a grower contract might not be met with an early harvest, further reducing potential profits for farmers (Curtis, 2003).

Early harvest can hinder the formation of periderm on the surface of the potato. Periderm, or skin, is the cork-like material that provides protection from dehydration, handling damage, and diseases (Sabba *et al.,* 2007). The periderm is comprised of three layers, the phellogen, the phelloderm, and the phellem. The phellogen is the meristematic region where skin cells divide as the tuber grows (Vreugdenhil & Bradshaw, 2007). Phellem is a layer of five to six tiers of cells to the outside of the phellogen that were produced by the phellogen. The tiers of phellem cells are stacked like bricks to form a hardened layer of skin (Vreugdenhil & Bradshaw, 2007). Phelloderm is a layer found to the inside of the phellogen and provides raw materials for the phellogen to form the phellem and subsequent skin (Vreugdenhil & Bradshaw, 2007). Due to natural senescence or vine kill, the tuber stops growing. This initiates the process of skin setting in which the meristematic region of the phellogen stops producing new cells and the phellem region thickens, hardens and suberizes (Vreugdenhil & Bradshaw, 2007). The entire periderm becomes bound to the underlying tissues of the tuber, making it resistance to the shearing of the skin, also known as skinning. However, when the potatoes are harvested early, the periderm formation, specifically the phellem, is interrupted and an inadequate, immature layer is formed (Lulai, 2002). The layers of the phellem are underdeveloped and are easily damaged.

Another physiological disorder relating to periderm formation can occur. Known as “skin slip” this condition is the peeling of layers of the fragile new skin off of a tuber and is a result of harvesting a potato before its skin has completed development. (Lulai, 2002) The feathering, peeling layers of skin is considered a serious quality defect. Skin slip is of particular concern to growers who grow and sell thin-skinned varieties of color to the fresh market for customers seeking vibrant colors (Lulai, 2002).

For processors, skin slip may be tolerable for potatoes being quickly processed, however there could be compromises in quality. One of the first consequences of inadequate skin development is moisture loss from the tuber, causing a reduction of the weight of product available to be processed (Sabba *et al.,* 2007). Tubers harvested too early can experience significantly more moisture loss than those harvested at physiological maturity (Castleberry & Jayanty, 2012). If a grower has yet to sell his product to the processors, moisture loss results in economic loss as they now have less product to sell. The lack of protective peel also increases the likelihood of tuber bruising and handling damage causing visual quality issues during the processing stages, again resulting in economic losses (Bethke & Busse, 2010).

The lack of an intact protective skin due to harvest damage leaves the tuber vulnerable to a variety of storage diseases (Smittle *et al.,* 1974). The most common of these diseases is Pectobacterium soft rot, Bacterial Ring Rot, Fusariam dry rot, Pink rot, Pythium leak, late blight, and early blight (Hooker, 1981). Most fungi that attack tubers are found naturally in the soil, although some sites of fungal infection include infected seed pieces, cull piles or volunteer potatoes in the field. When potatoes enter storage, some soil is shaken off during the harvest and sorting process, but not all is removed. Therefore, the fungi enter the storage with the soil (Secor & Gudmestad, 1999). With thin-skinned varieties or with a compromised skin due to harvesting damage, the fungus can easily penetrate the potato flesh (Secor & Gudmestad, 1999). Secondary opportunistic microbial infection, such as with Pectobacterium soft rot, can also occur once an invasive route into the tuber has been established by the fungal penetration (Olsen, 2014).

Potatoes from early harvest exhibit an increase in the rate of respiration which can persist in storage for 3 to 4 months after harvest (Bethke & Busse, 2010). Studies conducted by Bethke and Busse show an increase in respiration rates of early harvested potatoes by 18 to 25%. Heltoft *et al*., (2010) research showed an increase in respiration rate with a corresponding increase in weight loss and lower dry matter over a six month storage season with immature potatoes. They concluded that a poor skin set with resulting skinning injuries increased both respiration and transpiration (Heltoft *et al.,* 2016). Increased respiration results in the production of CO2, water and heat energy being generated from the conversion of starch to sugar in the tuber (Liu *et al.,* 2003). Temperatures may increase within a storage due to the increased respiration of the potatoes. When the dew point is reached within a storage, water vapor will condense to form liquid dew (Pringle, 1996). Water forms on the surface of the potato as the result of condensation, i.e. the formation of water droplets when moist air is cooled. In potato storages, this occurs when warmer, respiring potatoes are exposed to previously cooled potatoes or to cooler air (Pringle, 1996). This can create a favorable environment for further disease formation (Olsen, 2014). Heat energy is a concern since this can drive up the temperature of a storage and contribute to additional disease formation as well as initiate sprouting (Bethke & Busse, 2010).

Physiological aging of seed tubers as a result of increased respiration has been noted by Blauer *et al.,* (2013). Physiological aging differs from chronological aging in that physiological aging is the accumulation of biochemical changes that occurs as a result of stressful growing or storages conditions, such as temperature stress, moisture stress, disease and insect pressure, harvest damage, and storage mismanagement (Gould, 1999). Chronological age is simply the number of days since the potatoes were harvested (Gould, 1999). Increased respiration rate of tubers due to high temperature priming increases the physiological age of the potato (Blauer, *et al.,* 2013). Early harvest, as previously stated, increases respiration and has potential to increase the physiological age of early harvested tubers.

Harvest timing can also impact specific gravity and thus, impact end-product quality. This is due to the relationship between photosynthetic activity in the field, sucrose production within the leaves of the plant, and the translocation of surplus sucrose to the tubers where they are converted in to starch (Nakamura, 2015). Factors that limit plant growth, such as air and soil temperatures, climate, and a reduction in growing days, also limit sucrose production and therefore limits eventual conversion of sucrose to starch (Nakamura, 2015). Potatoes harvested at the peak of physiological maturity have had an adequate number of growing days in the field, providing the plant with sufficient photosynthesis to generate sucrose that is converted into starch within the tubers (Driskill, *et al.,* 2007). These potatoes tend to have the highest specific gravities and tend to produce the highest quality French fries (Driskill *et al.,* 2007). However, an early harvest of potatoes can negatively impact specific gravities due to a reduction of days in the field needed to not only generate sucrose from photosynthesis, but also to also convert that sucrose to starch within the tuber (Gould, 1999).

Advantages of Late Harvest

Late harvest in potatoes is regarded as harvest past the point of physiological maturity, i.e. leaves and vines are in advanced stages of senescence, skin set is nearly complete, and maximum yield has been achieved (Wohleb *et al.,* 2010). As an additional indication of over maturation, studies have shown an increase in sucrose content and a reduction in specific gravity with overly mature potatoes (Driskill *et al., 2007)*. Late harvest has its own set of advantages and disadvantages in comparison to early harvest with regard to securing high quality potatoes that will eventually produce acceptable end-products. Depending upon the variety, a delayed harvest with late maturing cultivars can provide additional time needed to increase overall yield (Debuchananne & Lawson, 1991; Solaiman *et al*., 2015). Studies indicate that tuber bulking continues until either vine kill or natural senescence occurs, thus increasing tuber yield by extending the bulking period (Narasimhamoorthy *et. al*., 2013). Since the farmer is paid by weight, this potentially increases the farmer's profits (Guenthner, 1995).

A later harvest also enables potatoes to reach the larger size categories often desired by processors in order to meet their retail customer's demand for long fries (Gould, 1999). The larger potatoes normally possess a greater length allowing them to process into the longer French fries often preferred by the end-use customer (AMS, 2015). Grower contracts frequently provide incentives for potatoes above 170 grams, enabling growers to increase their profits. (Curtis, 2003)

Harvesting later in the season improves the skin set, i.e. the maturation of the periderm on the tuber, of the potato crop by allowing the plants to senesce naturally or allowing suitable time for vine kill and skin set in the field (Sabba *et al.,* 2007) . Potatoes with a good skin set have greater protection against moisture loss in storage (Smittle et al., 1974). As stated earlier, farmers are paid by weight and reducing weight loss will help maintain profits (Curtis, 2003). A good skin set will also reduce the likelihood of fungal and microbial pathogen infections, reducing the overall occurrence of disease within the stored crop (Secor & Gudmestad, 1999).

Harvest timing also impacts specific gravity, which is a critical element of determining texture of processed French fries (Sayre *et al.,* 1975). A crop that has achieved physiological maturity or a moderately late harvest crop tends to have higher specific gravity, producing a much higher quality end-product (Singh & Kaur, 2009). Furthermore, meeting certain specific gravity parameters is considered a positive attribute and is stated in most grower contracts. (Curtis, 2003) When farmers are able to meet those specific gravity standards, they have the potential to increase profits (Curtis, 2003). However, studies have shown that overly mature potatoes can have a decrease in specific gravity due to the conversion of stored starch within the tuber back to sucrose in response to late season heat stress (Bethke & Busse, 2010).

<u>Disadvantages of Late Harvest</u>

Potatoes harvested later in the season are also physiologically older and have possibly experienced more stress (Kissmeyeer-Nielsen & Weckel, 1967). Stressful events, such as late season temperature extremes, often increase the sucrose content of the potatoes, potentially darkening fry color (Bethke & Busse, 2010). Potatoes harvested at the end of the season have been shown to increase in overall sugar content once physiological maturity has been reached, again negatively impacting fry color (Sabba *et al.,* 2007).

Dormancy in storage is also affected by harvest timing. Research by Driskill *et al.,* 2007 showed that older and more mature tubers broke dormancy earlier than younger and less mature potatoes (Driskill *et al.,* 2007). In addition, studies conducted by Mani & Hannachi*,* 2015 indicated that physiological development of late harvest potatoes could be accelerated, increasing the likelihood of sprouting in storage (Mani & Hannachi*,* 2015*)*. Even potatoes with long storage dormancy may experience earlier sprouting than those harvested at the peak of physiological maturity (Struik, 2007). Sprouting in storage can result in water loss within the potato, reducing the overall weight of the potatoes. This will negatively impact the amount of potatoes available for processing as well as the overall price of the potatoes (Guenthner, 1995).

Farmers also tend to gamble with weather by harvesting later. Rains associated with fall weather can contribute to lenticel swelling and the introduction of pathogens (Secor & Gudmestad, 1999). Rain can also complicate harvest timing due to equipment constraints (Smittle *et al.,* 1974). Chilling and freezing tubers can thoroughly damage an entire crop, rendering it unsuitable for sale or storage (Stark & Love, 2003).

Tuber specific gravities can be negatively impacted by a late harvest. When potatoes remain in the ground following vine death, starch can be converted to sugar as the potato respires (Bethke & Busse, 2010). Studies have shown that this situation occurs most often when potatoes are exposed to high soil temperatures (Hertog *et al., 1997)*.

POTENTIAL FACTORS AFFECTING TEXTURE OF FRENCH FRIES AND THE RELATIONSHIP TO HARVEST TIMING

Previous sections of this chapter discussed harvest timing factors that had the potential to negatively impact overall end-product quality. The focus of this section pertains to factors associated with harvest timing that specifically impact French fry texture.

Specific Gravity

Specific gravity is considered the most important contribution to French fry texture and impacts all aspects of both the internal and external features of French fry texture (Miranda and Aguilera, 2006). Specific gravity is the measurement of the density of the potato using a starch to water ratio. Higher specific gravity generally indicates that the potatoes have a higher starch content and therefore will have greater interaction with the frying oil and subsequent release of water from the potato (Rossell, 2001). Potatoes with a high specific gravity will tend to produce French fries with a crisp outer shell with lightly firm exterior shell, a fluffy, light interior with a pleasing level of moistness (Sayre, *et al.,* 1975; Solomon & Jindal, 2005). The visual appearance is also impacted by specific gravity. French fries produced from potatoes of high specific gravity will tend to have a lightly cooked appearance with a slight hollowing from the edges of the fry (Gould, 1999). However, French fries produced with low gravity potatoes will have a weak exterior shell lacking crispness (Sayre *et al.,* 1975). The mealiness also will be lacking and instead the fry will be creamy and smooth with excessive moisture. The interior of the fry will be raw-looking with no degree of hollowing (Kita, 2002; Jaswal, 1969). Specific gravity can also be too high. French fries from excessively high specific gravity will have a tough exterior shell, dry mouthfeel, and a hollowed-out appearance (Kita, 2002; Sayre *et al.,* 1975).

Starch Composition

The starch in potato tubers is rather unique in the plant kingdom. The molecular structure of potato starch is a large, with a smooth granular shape (Fennema, 1996). These individual and distinct granules vary in size from 10 to 100 micro millimeters (Singh & Kaur, 2009) which is considerably larger than rice, corn, or wheat with average granule sizes of 5.5, 9.8, and 6.5 micro millimeters respectively (Fennema, 1996). Amylopectin, a highly branched macromolecule, is the key component of potato starch, constituting 70 to 80% by weight (Singh & Kaur, 2009). Amylose is the other building block of potato starch and is a much smaller molecule than amylopectin, and is linear in shape (Liu *et al.,* 2003). The highly organized and dense structure of potato starch renders it less likely to succumb to enzymatic degradation (Jaswal, 1969). This structural component allows potatoes to be cooked in a variety of ways while maintaining its desired structural integrity as an end-product (Liu *et al.,* 2003).

Harvest timing can negatively impact the size of the potato starch granule, which can reduce end-product quality. Generally, large starch granules are preferred for processing due to their greater capacity to swell when cooked (Singh & Kaur, 2009). Harvesting too early can produce potatoes with smaller starch granules (Noda *et al.,* 2004). These granules are unable to absorb water within the cell and instead, the end-product lacks crispness, the exterior shell lacks structural integrity, and the mealiness may be too smooth (Gould, 1999). The overall moistness of the fry will be too high and the visual appearance will portray a raw, uncooked product (Rossell, 2001).

Non-Starch Polysaccharides and Phenolic Polymers

Potatoes of high specific gravity are expected to produce high quality French fries, however specific gravity alone is not the only defining element of pre-determining textural quality (Lisinska & Golubowska, 2005). Studies have shown that potatoes of similar specific gravity exhibit varying levels of textural acceptability (Kita, 2002). Specific gravity is a critical aspect of French fry quality, however, other components of the potato can alter textural quality significantly. These include the non-starch polysaccharides, NSP, of cellulose and pectins, and phenolic polymer known as lignin (Kita, 2002).

Cellulose is a major component of the plant cell wall, conveying strength and rigidity to the tri-layered cell wall (Fennema, 1996). The integrity of the cell wall is a vital component of texture in that maintains compartmentalization of intracellular components and prevents degradation by enzymes (Liu *et* al., 2003). This non-starch polysaccharide can contain up to 12,000 glucose units, forming dense fibrils which wrap into compact bundles. Cellulose interacts highly with lignin, a phenolic polymer which produces secondary thickening and additional reinforcement of the cell wall (Fennema, 1996). Outside of the cell wall, pectins forms the adhesive which hold adjacent cells together. This area is known as the middle lamella and functions further to provide stability to the cellular matrix (Liu *et al., 2003)*.

The structural integrity of NSP and lignins of the potato are highly important for French fry textural quality (Liu, *et al.,* 2003). Maturity at harvest further affects the relative proportions and contents of the cell wall constituents (Fennema, 1996). Weakened cell walls tend to break down earlier in processing resulting in final product with poor texture (Fennema, 1996). Studies have shown that potatoes harvested prior to physiological maturity produce tubers with weaker cross linkages of the branched amylose pectins, (Jaswal, 1969) causing a higher percentage of broken linkages during frying (Golubowska, 2005). The lack of structural integrity of the middle lamella substantially weakens the cell wall, which may disintegrate during processing, thus producing French fries with poor interior texture (Liu *et al.,* 2003).

<u>Potato Tuber Size</u>

Harvesting processing varieties at physiological maturity normally provides potatoes with adequate tuber size to meet French fry size parameters (Stark & Love, 2003). Harvesting early can result in potatoes that are undersized, producing shorter than desired French fries that can fail to meet specifications set by both the processors and the buyers (Rossell, 2001). Shorter French fries often have a higher crispness score due to over cooking in the pre-set timed fryers found in foodservice stores (Rossell, 2001). Harvesting late can produce more tubers within the highly desirable > 170 grams size category. However, some varieties are known to produce very large tubers that exceed size parameters set by the processors (Mackerron & Davies, 1986). Regardless of specific gravity, a high percentage of excessively long French fries are known to produce limp fries with an oily mouthfeel due to a lack of uniform cooking during the final fry (Sekuler, 2004).

PHYSIOCHEMICAL CHANGES OF FRENCH FRIES DURING STAGES OF PROCESSING AND THE RELATIONSHIP TO HARVEST TIMING

The quality of incoming potatoes to the potato processing plant is the single most important feature to producing high quality French fries (Golubowska, 2005). Technological advances within the processing plants have made significant improvements in processing French fries, but the quality of the raw material remains the defining parameter (Golubowska, 2005). The potatoes are processed in a strict order of cooking states; blanching, drying, and frying, to a partially fried state, frozen, packaged, and delivered to buyers (Miranda & Aguilera, 2006). At the foodservice establishment, the pre-packaged French fries are fried again in pre-set timed fryers, and then sold to the final consumer (Rossell, 2001).

Each step of the French fry processing line creates anticipated physiochemical changes within the potato strip (Lisinska & Golubowska, 2005). The end result of these changes is a French fry product that meets customer demands for a light and crispy exterior with a fluffy and mealy interior (Gould, 1999). If there are structural deviations within the raw product due to harvest timing, stress, mishandling, or disease, the final product may not meet expectations (Fennema, 1996).

Potatoes entering a processing plant are first washed and graded (Gould, 1999). Potatoes meeting the size requirements to become French fries are steam peeled and any bruising is trimmed away (Gould, 1999). The potatoes are then cut to contract stated strip size and again evaluated for defects (Gould, 1999). The most pronounced changes in potato texture are derived from the following cooking steps, blanching, drying, partial frying and final frying (Lisinska & Golubowska, 2005).

After the strips have been evaluated for color defects, they enter the blanching step, which is a gentle non-boiling cooking stage of 60^{o} to $65^{o}C$ for 5 to 60 minutes (Rossell, 2001; Singh & Kaur, 2009). Blanching of the potato strips is done to inactivate enzymes, such as polyphenol oxidase, preventing enzymatic grey discoloration in the finished product (Rossell, 2001). The blanching step also protects the color of the finished product by washing out the reducing sugars, fructose and glucose, from the freshly cut potato strips so that the potential Maillard reaction between the sugars and available amino acids is decreased (Gould, 1999).

However, the primary function of blanching is to serve as the initial cooking step to create the interior of the French fry (Golubowska, 2005). During blanching, the starch granules begin to heat and vibrate, breaking the intermolecular bonds (Fennema, 1996). This allows the hydrogen bonding sites to interact with the free water found within the cell. The starch granule begins to swell at 60 – $70^{o}C$ due to starch gelatinization, i.e. the absorption of available water from within the cell (Fennema, 1996). At similar temperatures during the blanching step, the pectins of the middle lamella found between the cells begin to break down. The cells separate forming the distinctive and desirable interior mealiness texture of French fries.

In regards to harvest timing, potatoes harvested earlier than at physiological maturity tend to have the appearance of being overcooked at the blanching step (Gould, 1999). This is potentially due to the lower number and smaller size of the starch granules within the potato cell (Noda et al, 2004) and due to the weaker pectin bonds that form the middle lamella. This first results in a marked decrease in the amount of available water that can be absorbed within the cell and within the potato strip (Rossell, 2001) The remaining free water can later penetrate the exterior shell of the French fry following the final fry step (Miranda & Aguilera, 2006), creating limp and soggy final product (Jaswal, 1969). Second, the weaker pectin bonds of the middle lamella break down earlier and to a greater degree during the blanching step (Miranda & Aguilera, 2006). With the early disintegration of the middle lamella, more damage occurs to the surrounding potato cells with near to complete breakdown of those cells so that an undesirable smooth, creamy interior is produced (Rossell, 2001). Larger starch granules that are associated with a later harvest tend to experience gelatinization earlier in the blanching process and to a greater degree than smaller cells (Liu *et al*, 2003). More free water is absorbed sooner in the cooking process resulting less free water to penetrate the crust formation during the drying, partial frying or the final fry (Miranda and Aguilera, 2006). Potatoes harvested at physiological maturity or later will tend to have stronger structural bonding between the cellulose and lignins within the cell wall, exponentially increasing the strength of the cell wall (Fennema, 1996). The presence of additional pectins within the middle lamella fortifies the bonding between adjacent potato cells (Fennema, 1996). The cells then separate at the appropriate timing during blanching to form the desired mealiness without full disintegration to a creamy interior (Rossell, 2001).

The potato strips then undergo a drying step, which significantly aids in the creation of the desired outer crust of the French fry (Gould, 1999). As the potato strips are dried, the outer layers of the strip experience more evaporation of free water than the interior of the strip. The outer layers shrink with the moisture loss and the drying creates a rigid exterior, the beginnings of the exterior crust (Rossell, 2001). Potato cells with a higher level of cellular integrity can withstand this process to a greater degree (Golubowska, 2005) and form an intact crust with cracks and crevices that allow for deeper oil penetration during the frying steps (Miranda & Aguilera, 2006). Potatoes with a higher specific gravity will tend to have less free water present in the outer layers of the strip, enabling a dryer, firmer crust to be formed. Again, potatoes harvested at or near physiological maturity will tend to have both cells with higher structural integrity as well as a higher specific gravity (Liu *et al*., 2002).

Frying is regarded as the most critical cooking step in French fry processing. It is at this stage that the outer crust is formed and that the interior of the fry achieves the desirable fluffy, mealy interior (Rossel, 2001). Several events are occurring simultaneously during the frying step. First, the frozen strips are submerged into the hot oil (160^{o}C to 180^{o}C) and heat transfer via convection takes place (Miranda & Aguilera, 2006). Within the external layers of the strip, water boils at 100^{o}C and evaporates almost instantly, drying out the exterior portion of the strip and creating the dry porous outer crust (Rossell, 2001). Inside the core of the strip, starch cells swell with available water uptake. The potato cells are heated and cooked via conduction, become disengaged from the middle lamella and form the distinctive mealy interior of a French fry (Miranda & Aguilera, 2006; Figures 1 and 2). Potatoes with a high specific gravity tend perform the best under these intense conditions, however, it is important to remember that potatoes of similar specific gravities can yield very different fries (Kita, 2002). The starch granules must be of sufficient size and number to absorb the free water within the potato cell (Liu, 2003). In addition, structural integrity of the pectins associated with the middle lamella must be structurally sound and able to withstand the intense cooking extremes of French fry processing (Miranda & Aguilera, 2006).

FRENCH FRY END PRODUCT QUALITY AS DEFINED BY TEXTURAL ATTRIBUTES

End product quality is analyzed by a variety of measurements to ensure that the desired product meets specific processing standards (Gould, 1999). Fry color, taste, and texture are considered to be the main sensory characteristics that French fry consumers value (Singh & Kaur, 2009). Numerous methods, both subjective and objective, exist to evaluate and score fry color, taste, and texture. Fry color can be analyzed using the simplest method of using a USDA fry color chart to computerized vision systems (Sayre, *et al.,* 1975). Flavor volatiles, such as heptanol, octanol, octenol, and methylnaphthalene, can be chemically analyzed (Rossell, 2001). The unique human perception of texture is often quantified through the subjective method of sensory evaluation, which is defined as “A scientific discipline used to evoke, measure, analyze, and interpret reactions to those characteristics of foods and materials as they are perceived by the senses of sight, smell, taste, touch, and hearing” (Stone, et al, 2012).

Evaluation of French fry texture employs the stimulus and use of all of one’s senses (Civille & Oftedal, 2012). The smell of hot oil triggers expectations and memories of consuming crispy, crunchy food (Stone, et al, 2012). The sight of the French fries provides an instant evaluation of texture based upon the presence of firm or limp fries and/or light golden brown fries or burnt fries (Miranda & Aguilera, 2006). The sense of touch is utilized by the consumer to evaluate texture when they detect a firm, dry outer crust or a soggy, greasy, wet fry (Miranda & Aguilera, 2006). Within the mouth, touch determines the level of moisture within a fry as the moisture is felt by the tongue, gums, and cheek walls (Stone, et al, 2012). The sense of sound is paramount to evaluate for texture since the acoustics of crispness within the mouth is experienced at nearly the same time as the teeth penetrate the fry (Salvador, 2009). Taste provides the final feedback for texture with the detection of positive notes, such as the satiating taste of oil, salt, and cooked potatoes or with the detection of negative notes, such as raw flavors, burnt flavors, or excessive oiliness (Sekular, 2004).

Texture analysis of French fries remains an elusive parameter without industry-wide standard measurements (Golubowska, 2005). Various machines and devices have been used unsuccessfully to quantify, measure and classify the uniquely human sensation of mouthfeel (Du Pont *et al.,* 2007). The textural experience of consuming a French fry is a distinctively personal experience for each consumer. Factors, such as the age and ethnic background of the consumer and regional preferences can alter acceptable texture definitions (Guenthner *et al.,* 1991). Physiological differences between individual consumers can also vary the textural experience. These include the saliva content within the mouth, age, and number of teeth of the consumer, and even one's general state of health. (Sekuler, 2004)

The evaluation of texture is further complicated by the fact that French fries are comprised of two distinctly different components, each requiring separate assessment scoring (Du Pont *et al.,* 2007). First, there is the external shell, which is the outer dehydrated, yet crispy layer of the French fry. (Singh & Kaur, 2009). This single component is considered by many to be the most important aspect of the French fry eating experience (Rossell, 2001). This first contact of the fry consists of the consumer experiencing a light crisp sensation as the front teeth break the outer fried shell (Sekuler, 2004). The second element of the French fry is the interior of the fry, which has completely different properties from the exterior shell that make it desirable to consumers (Miranda & Aguilera, 2006). The interior of the perfect French fry is expected to have a cooked, although fluffy, mouthfeel experience (Miranda & Aguilera, 2006).

Numerous scales have been created to quantify the experience of consuming a French fry. The most widely used food evaluation scale is the 9-point hedonic scale in which 1 is less preferred and 9 is highly preferred (Peryam & Pilgrim, 1957). This type of scale is a 2-dimensional evaluation of the food being consumed because it lacks information regarding how the score was obtained. The researcher has determined what the consumer prefers, but the hedonic scale does not provide data as to why the consumer prefers one product over another (Peryam & Pilgrim, 1957). To obtain information regarding specifics of sensory evaluation, several food companies adopted the "Just About Right" scale. This scale not only rates the consumer's preference of the product, but also evaluates the product on individual attributes that contribute to the sensory experience. (Popper & Kroll, 2005).

For this study, a variation of the McDonald's French fry "Just about right" scale was used. (J. R. Simplot, 2012). Four textural attributes and three visual attributes were analyzed on a 9 point "Just About Right Scale" in which 5 was the perfect score. The attributes included crispness, exterior shell, mealiness, moistness, textural variation, texture defects, and visual appearance. A score of 5 is considered to be the target score and is achieved only when that parameter meets all expectations for a perfect textural experience. One point on either side of the score of 5, a score of a 4 or 6, is generally considered acceptable by most processors for textural quality. A score of a three or a seven can be acceptable by some processors, but such standards would be stated in the purchasing contract of the chain or restaurant. Scores of 1, 2, 8, and 9 indicate that the product is below quality standards and unacceptable for release from the processing plant.

In evaluating French fries, the first textural attribute to be analyzed is crispness. This is the first physical sensation of mouthfeel that the consumer will experience and is considered by many to be the most critical for having a satisfying French fry experience (Miranda & Aguilera, 2006). Regardless of the scores of the remaining attributes, if the experience of crispness is absent, the total French fry experience will be negatively impacted (Sekuler, 2004). To achieve the most perfect French fry eating sensation, the consumer is to experience a light crunch sensation as the teeth bite into the exterior shell (Miranda & Aguilera, 2006).

The second French fry textural attribute is exterior shell. After the panelist has evaluated for the initial crispness score, the firmness of the exterior shell is evaluated. The exterior shell is to have a light, but firm single pulling action from the teeth (Sekuler, 2014). A fry that is too weak and lacks integrity is a negative consumer experience as is a fry that has a tough exterior shell and requires a degree of pulling for consumer to complete the biting action (Miranda & Aguilera, 2006).

Mealiness is the third textural attribute that is evaluated. This score, however, varies depending upon the restaurant's specifications. Some chains and restaurants prefer a light baked potato interior while other end-use customers prefer a smoother "mashed potato" interior (Rossell, 2001). The choice of potato variety, blanching and frying conditions within the processing plant and final fry preparation within the restaurant or food service chain further determine the mealiness of the French fry product (Du Pont *et al., 1992*).

Moistness of a French fry is the last of the subjective physical evaluations to be conducted when analyzing texture. It corresponds closely with mealiness, but is also its own defining feature. Similar to the mealiness score, this characteristic is scored based upon the retail or food service operation standards (Rossell, 2001). End users that prefer a baked potato interior will have a perfect score of 5 that corresponds more closely to a drier mouthfeel, whereas a customer who has specifications for a more mashed potato interior will have the perfect score of 5 that is associated with slightly higher moisture content (Sekuler, 2004). Again, the textural training traits for this experiment followed procedures for a baked potato feel. Therefore, taste panelists were asked to score a perfect 5 to a slightly drier scale.

Texture variation is based on the visual review of the sample just analyzed. From the consumer's point of view, this would involve evaluating the uniformity of the French fries that they had purchased. A positive experience occurs when the fries are all at acceptable or highly acceptable levels for each attribute (Rossell, 2001). A negative experience occurs when it is perceived that the fries are not uniform with regard to texture, such as having a higher than desired number of limp fries or over-cooked, crunchy fries (Rossell, 2001). Customers can perceive textural variation as a lack of product quality or as a reduction in the restaurants standards of food preparation and quality (Guenthner *et al.,* 1991).

Texture defects include negative textural traits that a consumer would immediately find undesirable. These include greenness, oiliness, limpness, burnt, and crunch (Sekular, 2004). A texture defect can be profoundly negative for a consumer, who may judge the entire experience based upon the texture defect of one to five fries. That negative judgement of the French fry experience can be transferred to a negative perception of the entire restaurant or food service chain and discourage repeat business (Guenthner *et al.,* 1991).

Internal visual appearance is not considered a texture analysis trait, but rather it is a visual analysis of the interior of the fry to determine how completely it is cooked (Miranda

& Aguilera, 2006). This indirect visual analysis is often used in place of a textural analysis to determine if the fry is fully cooked through and has achieved the desired texture (Rossell, 2001). A French fry product that has specifications for a baked potato interior appearance would have a drier interior appearance with a small percentage of hollowing. A French fry product that has, instead, specifications for a mashed potato interior would have a moister, smooth internal appearance with little to no hollowing (Du Pont *et al.,* 1992).

The major French fry processing companies have internal, trained taste panelists who score their product for flavor, aroma, texture, and appearance (Sekular, 2004). Panelists must possess the ability to detect off-odors and off-flavors as well as characterize the issue for analysis (Sekular, 2004). The panelists must also maintain the acceptable profile for the analyzed product and must not apply their own personal preferences to the product (Du Pont *et al.,* 1992).

POTATO VARIETIES CHOSEN FOR STUDY

Three French fry processing potato varieties were chosen for the study and were assumed to be similar in producing an end-product that met industry quality standards. Russet Burbank, considered the industry standard for texture and flavor by major restaurant chains, was selected as a baseline of acceptable sensory characteristics (Bethke *et al.,* 2014). Clearwater Russet and Alpine Russet have both showed potential as processing varieties in earlier agronomic and processing trials and therefore were chosen for this study to provide comparisons with Russet Burbank.

Russet Burbank

Russet Burbank has been the industry standard potato variety for processing for decades and is still the most widely grown processing variety in the United States (Bethke *et al., 2014).* It is late maturing and has long tuber dormancy, which allows it to be processed over a relatively long storage season (Bethke, *et al.,* 2014). However, Russet Burbank has many defects such as a tendency to produce low percentages of U. S. No. 1 tubers due to excessive numbers of small or misshapen tubers and inconsistent processing quality due to low specific gravities, high percent sugar ends, and dark colored fries when exposed to heat or water stress (Bethke, *et al.,* 2014).

Alpine Russet

Alpine Russet possesses numerous traits that make it acceptable as a processing variety. Within the Tri-State trial locations, Alpine Russet outperformed Russet Burbank in total yield and the percent U.S. No. 1 yields. The Alpine Russet had fewer culls and U.S. No. 2 tubers, and fewer rotten and misshapen tubers when compared to Russet Burbank (Whitworth *et. al.,* 2011).

Alpine Russet has exhibited the ability to maintain excellent fry color through-out long term storage (Whitworth *et al.,* 2011). Earlier studies indicated that the Alpine Russet had higher sucrose levels than Russet Burbank, which would normally lead to unacceptable fry color. However, Alpine Russet has low levels of invertase, the enzyme responsible for hydrolyzing sucrose to the reducing sugars glucose and fructose and therefore, the fry color is not negatively impacted (Whitworth *et al.,* 2011). Additionally, studies have shown that Alpine Russet has consistently lower glucose levels than Russet Burbank throughout a full storage season at temperatures of 5^{o}C, 7^{o}C, and 9^{o}C (Whitworth *et al.,* 2011). Alpine Russet also displays resistance to sugar end disorder development. Studies showed that when compared to Russet Burbank, Alpine Russet consistently had lighter and more even fry color throughout the storage season (Whitworth *et al*., 2011).

Alpine Russet possesses another highly desirable feature in that it maintains long tuber dormancy in storage before peeping and sprouting occurs. Studies have shown that the Alpine Russet has a slightly longer dormancy than Russet Burbank by approximately 10 days when stored at 5^{o}C, 7^{o}C, and 9^{o}C (Whitworth *et. al.,* 2011).

Alpine Russet does exhibit higher susceptibility to Fusarium dry rot in storage than Russet Burbank, however, this can be managed with good harvest and storage practices (Whitworth *et. al.,* 2011).

Clearwater Russet

Clearwater Russet is a versatile potato that is acceptable for both processing and fresh pack. It possesses a lightly russeted skin with shallow eyes and an oblong uniform shape and size (Novy *et al.,* 2010). Total yield is similar to Russet Burbank with a high percentage of US No. 1 potatoes, although the size distribution can be smaller. This can be managed by increasing seed piece spacing in the field (Novy *et al.,* 2010).

Studies have demonstrated that Clearwater Russet maintains excellent fry color over a 9 month storage period. Glucose levels remained low throughout that time period with a <0.08% at 5.5^{o}C, <0.05% at 7.2^{o}C and again, <0.05% at 8.3^{o}C. Sucrose levels are similar or less than Russet Burbank for the storage season (Novy *et al.,* 2010).

Resistance to sugar end development is another desirable characteristic of Clearwater Russet. In studies conducted at the University of Idaho Kimberly Research Station, Clearwater Russet exhibited lighter stem-end fry color than Russet Burbank when tested over a three year period of time at temperatures of 5.5^{o}C, 7.2^{o}C, and 8.3^{o}C (Novy *et al.,* 2010).

Another notable positive characteristic of Clearwater Russet is its protein content, which is about 35% higher than Russet Burbank. This variety also has high specific gravity and displays excellent resistance to sugar ends, even when exposed to stressful growing conditions (Novy *et al.,* 2010).

Clearwater Russet possesses the highly desirable trait of cold temperature sweetening resistance, enabling it to be stored at lower temperatures without developing reducing sugars that can produce undesirably dark fries (Novy, *et al.,* 2010). Additional studies further indicate that the cold sweetening resistance of Clearwater Russet translates into exceptional French fry color for full storage season (Novy *et al.,* 2013).

Clearwater Russet exhibits susceptibility to *Fusarium sambucinum* to a higher degree than Russet Burbank. Additional care is recommended during harvesting to reduce the likelihood of this diseases introduction (Novy *et al.,* 2013).

An additional trait of concern is the short dormancy that Clearwater Russet exhibits in storage. Studies show that when stored at 5.5°C, 7.2°C, and 8.9°C, this variety broke dormancy 55 to 65 days earlier than Russet Burbank (Novy *et al.,* 2013).

RESEARCH OBJECTIVES

French fry end-product quality has been evaluated using the USDA fry color scoring system and the mechanical examination and internal visual appearance of cooked product (USDA AMS, 1967). Additional information about the impact of harvest timing on textural parameters of end-product quality is needed within the industry. The objective of this study is to determine if harvest timing has significant influence on French fry texture over the course of a full storage season, and if that that influence exists, which textural characteristics are affected and to what degree. An economic evaluation was also incorporated into the study to determine if harvest timing affects the incentive adjusted price of a grower contract.

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Figure 1. Scheme of heat and mass transfer during frying and the prevailing temperatures and moisture profiles. (Miranda & Aguilera, 2006)

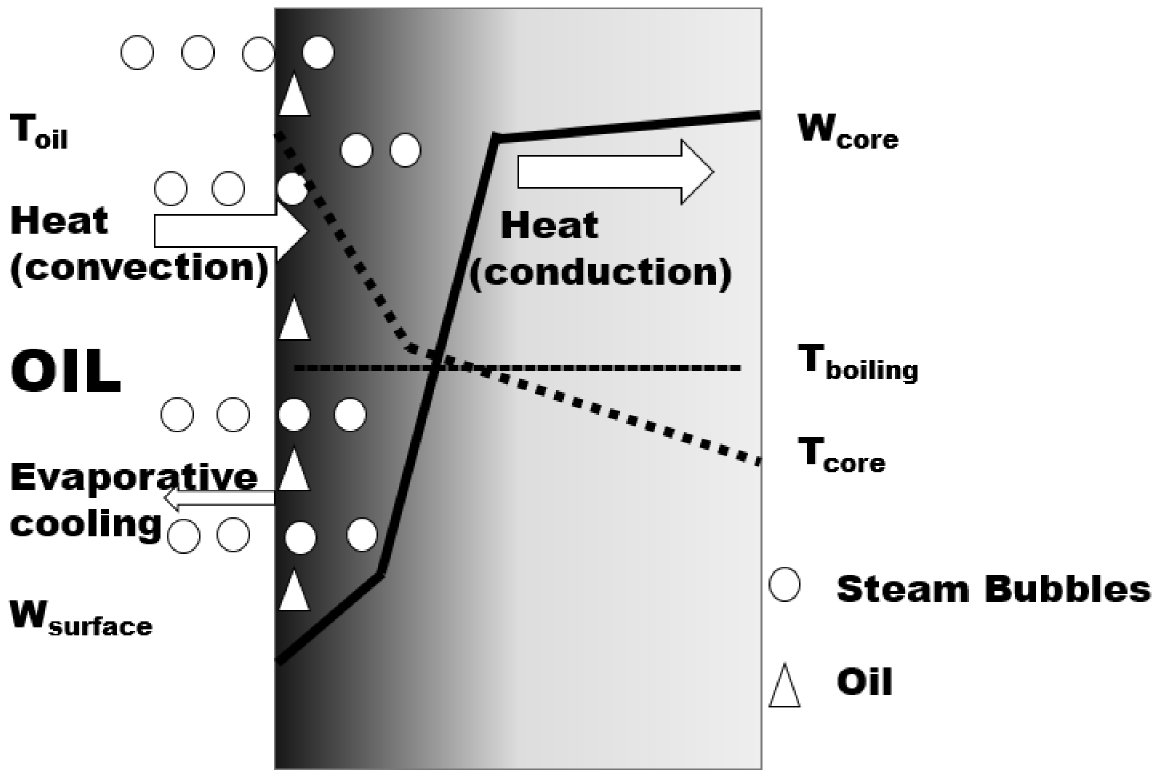
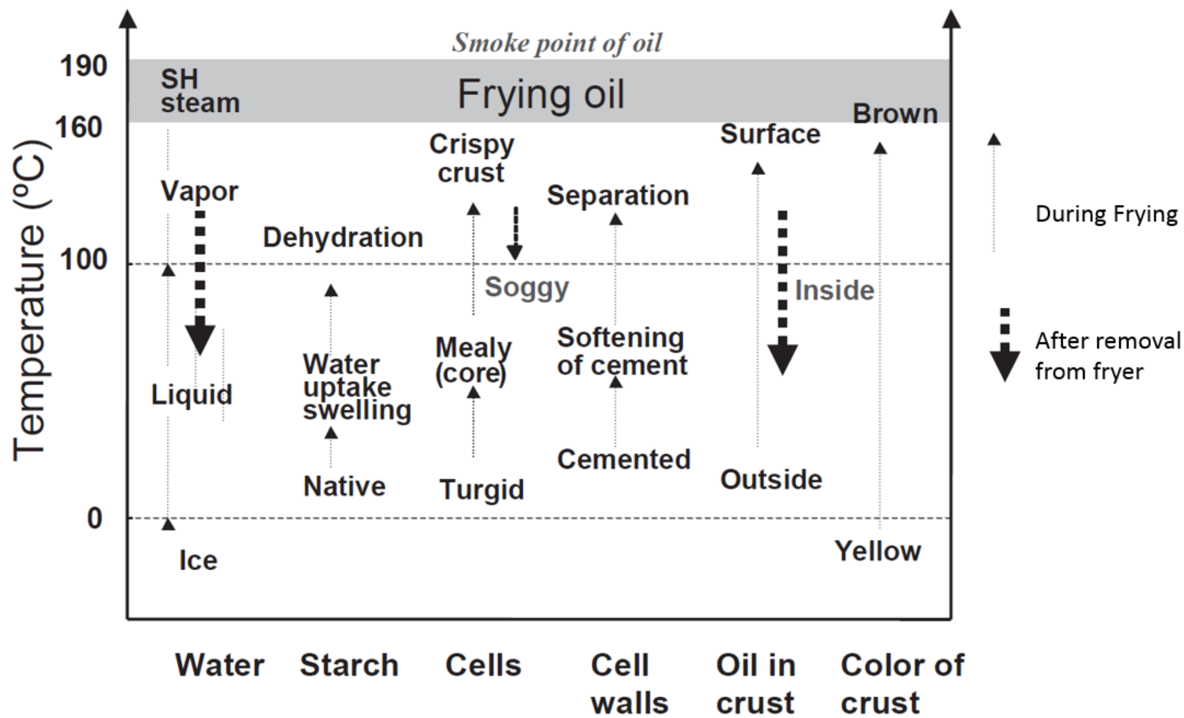


Figure 2. A scheme of physical, chemical, and structural changes occurring during frying of potatoes due to temperature. (Miranda & Aguilera, 2006)



CHAPTER 2: AN ECONOMIC ANALYSIS OF THE EFFECTS OF HARVEST TIMING ON YIELD, QUALITY, AND PROCESSING CONTRACT PRICE FOR THREE POTATO VARIETIES

ABSTRACT

It is well established that harvesting potatoes at or near physiological maturity increases the production of high quality tubers, which will in turn, produce higher quality processed end-product. However, many growers are harvesting earlier than recommended in order to meet their contracts and supply processors with early potatoes. Consequently, this pressure to harvest early can impact the incentive-adjusted price (IAP) and revenue even after an early harvest incentive is applied. This study utilized a mock contract and compared the economic impact of harvest timing (prior, at, and past physiological maturity) on the IAP of three potato varieties, Russet Burbank, Clearwater Russet, and Alpine Russet, grown in field trials at Parma, Idaho during 2014 and 2015. In addition to yield, the contract quality incentives included in the economic analysis were the percentage of tubers greater than 170 grams, percent sugar ends, percent of U.S. No. 1's, and specific gravity. Early harvest incentives were also applied. Harvesting prior to physiological maturity resulted in a decrease in the IAP and overall profit due to a significant reduction in specific gravity. Early harvest incentive did not offset the loss of revenue with Russet Burbank, but did offset revenue loss with Clearwater Russet and Alpine Russet. The study revealed the potential that new varieties have for increasing the IAP. Clearwater Russet and Alpine Russet had significantly lower sugar end scores than Russet Burbank. Clearwater Russet consistently produced higher specific gravities and Alpine Russet produced larger tubers compared to Russet Burbank, both resulting in an increase in the grower profit. Overall, Clearwater Russet and Alpine Russet have agronomic characteristics that can provide an increase in IAP over Russet Burbank.

INTRODUCTION

Harvest timing is of particular concern to both growers and processors as they prepare their schedules for harvest and processing. Harvest timing can impact several parameters of a grower contract, including yield, tuber size, specific gravity, and fry color

(Solaiman *et al., 2015)*. Early harvest has been shown to produce crops with lower total yield, smaller potatoes that may not meet size parameters of the grower contract, and lower specific gravities (Driskill *et al.,* 2007; Narasimhamoorthy *et al.,* 2015). Delaying harvest may allow growers to reach higher total yield, larger potatoes that meet the desired >170 gram parameter, and higher specific gravities (Driskill *et al.,* 2007; Gould, 1999; Narasimhamoorthy *et al.,* 2013). For growers, the effect upon these parameters can significantly increase or decrease the IAP, affecting their overall profit. For processors, harvest timing may affect the quality of incoming raw product so that end-product quality is affected. Therefore, it is important both parties understand the impact of these decisions in order to make economically sound decisions (Wilson, 1986).

POTENTIAL IMPACT OF HARVEST TIMING ON CONTRACT PRICE OF POTATOES

Potato growers are paid by the weight of potatoes that meet the standards of the contract (Penson Jr. & Capps Jr., 2014). It is important to emphasize that a high yield does not guarantee the farmer a profit from the crop. The yield must also meet the quality criteria established within the contract (Curtis, 2003). However, contracts require a specific number of acres to be planted with an anticipated tonnage to be harvested. Therefore, total yield does offer some insight into potential profit for the grower and potential costs for the processors (Somsen & Capelle, 2002).

Harvest timing has a significant impact upon total yield and tuber size. Normally, potatoes harvested early, i.e. prior to physiological maturity as indicated by poor skin set, green vines, and higher sucrose levels, are smaller in size and weight (Narasimhamoorthy *et al.,* 2013). Growers receive a price discount if the potatoes are below the size and weight threshold, reducing profit (DeBuchananne & Lawson, 1991). Potatoes harvested at physiological maturity typically have acceptable size and normally meet contract parameters (DeBuchananne & Lawson, 1991). Harvesting at a later date generally increases total yield and has the potential to increase profit by achieving a higher proportion of tubers within greater than 170 grams. (Narasimhamoorthy *et al.,* 2013).

Frozen potato processing contracts detail acceptable standards for potato quality, thus increasing the likelihood of producing processed potato products that meet the stringent standards of end-use customers (Curtis, 2003). However, only 5 of the 9 stated parameters within the contract used for this study are significantly impacted by harvest timing. These include percent of U. S. No. 1's, specific gravity, tuber sizes, sugar ends, and fry color. In addition, early harvest incentives were applied.

U.S. No. 1 refers to potatoes that meet USDA standards and basic requirements including "similar varietal characteristics, moderately firm, and fairly well shaped" (USDA AMS, 2014). The potatoes must also be free from freezing, freezing injury, blackheart, late blight tuber rot, bacterial wilt, bacterial ring rot, insects, worms, larvae, soft rot, loose sprouts, dirt, and foreign material and the potatoes must be free from overall damage from any other causes (USDA AMS, 2013). Potatoes should not be smaller than 5cm in diameter or 113 grams in weight (USDA AMS, 2013).

Specific gravity is perhaps the most important indicator of potato quality. Potatoes with high specific gravity are known to produce French fries with the desired textural traits preferred by the end-use retail customer (Driskill *et al.,* 2007). Potatoes harvested early have lower specific gravity than potatoes harvested at physiological maturity or potatoes harvested later in the season (Singh & Kaur, 2009). Within the contract, this difference in specific gravity level is reflected on the sliding scale of additions or reductions in the Incentive Adjusted Price or IAP. For the processing contract used in this study, tubers with specific gravities lower than 1.078 have a reduction in IAP, whereas tubers with specific gravities over 1.080 have an increase in IAP (Wilson, 1986).

Tubers destined to become French fries should possess an oval shape with a high length to width (L/W) ratio, and size of at least 170 grams in order to meet the French fry length requirements of the retail restaurant customers (Si, *et al.*, 2016 and Gould, 1999). Harvesting early may reduce the amount of time that potatoes grow and bulk, thereby producing a crop of potatoes that may not meet minimum shape and size standards (DeBuchananne & Lawson, 1991). Late harvest usually produces tubers of adequate size, but can also produce tubers that are too large, creating a processing issue as some tubers may require additional cutting to provide the correct size for processing (Gould, 1999). The sliding incentive scale for size is based upon a percentage of the crop that is over or under 170 grams. Less than 60% of tubers (by weight) of > 170 grams results in a reduction in the IAP. For the contract used in this study, greater than 60% tubers of at least 170 grams increases in IAP, until 85% is reached and then deductions occur for over-sized potatoes (Wilson, 1986).

Tubers from early harvest tend to have higher sugars and can produce fries with a darker, less desirable color (Groves *et al.,* 2005). Tubers harvested at physiological maturity have low sugars and therefore, produce fries with a lighter, preferred color (Sabba *et al.,* 2007). As tubers age with a later harvest date, sugar contents can increase and have the potential to produce fries that are darker in color (Groves *et al.,* 2005). This impact of harvest timing on fry color is expressed in the contract as an acceptable percentage of fry strips within a certain range on the USDA color chart (Curtis, 2003). Early or late harvest may produce potatoes that have a higher percentage of darker color fries and therefore reduces IAP. Physiologically mature potatoes harvested at the optimal time should have the greatest likelihood of having acceptable color, thereby lessening the probability of a price reduction or rejection (Penson Jr., & Capps Jr., 2014).

Potato processing companies are aware of the potential negative economic effect that early harvest may have on a grower's revenue (DeBuchananne & Lawson, 1991) yet potato processing companies require an uninterrupted supply of potatoes year-round to meet consumer demand (Gould, 1999). To ensure a constant supply of potatoes, processing companies offer early harvesting incentives to offset the economic disadvantage incurred by an early harvest (Handayati, *et al.,* 2016). These incentives are designed to compensate growers for potential losses of early harvest, such as lower total yield, percent U.S. No. 1's, and specific gravities (Handayati, *et al.*, 2016).

OBJECTIVES OF STUDY

The objective of this study was to determine if harvest timing affects potato yield and quality and if so, to determine how those effects alter the incentive adjusted price (IAP) of a grower contract and whether the early harvest incentives offset the potential economic losses of an early harvest.

MATERIALS AND METHODS

The field portion of this study was conducted in 2014 and 2015 at the University of Idaho Research and Extension Center at Parma, Idaho on Greenleaf silt loam soil. The experimental design was a split-plot, randomized complete block design with four replications. The main plot treatments consisted of three separate harvest dates 1) early or prior to physiological maturity, approximately 2 weeks prior to normal, 2) normal or near physiological maturity, 3) late or past physiological maturity, approximately 2 weeks past normal. Maturity was determined by weekly senescence evaluations of the field. In 2014, this study was grown concurrently with a separate study called Acrylamide Agronomy Trial 2014-2015 that conducted periodic specific gravity measurements on Russet Burbank to estimate maturity. Those measurements aided this study in determining approximate maturity. Subplots were three processing varieties, Russet Burbank, Clearwater Russet, and Alpine Russet.

Each main plot was comprised of 6 sub-plots, 3.6 m (4 rows) wide X 12 m long, planted in 0.9 m-wide rows. Cut, untreated, certified seed pieces between 55 to 85 grams were planted 35 cm apart at a depth of 15-20 cm. Seed was planted using a two-row planter on April 15 in both 2014 and 2015.

Preplant fertilizer was applied at the rates of 45 kg N/ha, 224 kg P_2O_5/ha and 112 kg K_2O/ha in 2014, and 56 kg N/ha, 180 kg P_2O_5/ha and 112 kg K_2O/ha in 2015. A top dressing of 180 kg N/ha as NSN-urea was applied at hilling. All fertilizers and pesticides were applied according to University of Idaho recommendations.

Vines were mechanically removed with a rotary vine beater two weeks prior to harvest. Harvest dates ranges from 14 August, 2014 to 25 September in 2014 and 13 August to 21 September in 2015 (Table 2).

The tubers were lifted using a wind rower and then hand harvested into burlap sacks. Ten meter sections of row were harvested from the middle two rows in each plot. Tubers were sorted, graded, and weighed. A 10-kg sub-sample from each plot was used to determine specific gravity by the weight-in-air/weight-in-water method (Kleinschmidt et al., 1984). Grading consisted of weighing into the following categories; less than 113 g, 114 to 170 g, 171 to 283 g, 284 to 340 g, greater than 341 g, weight of #2's, and culls. The processing contract had specifications for only >170g. Therefore, the size categories of 170 to 283g, 284 to 340g, and greater than 341g, were added together to create the greater than 170g size category.

The remaining tubers from the rows were then placed into color coded and labeled 25 kg pound mesh bags, loaded into 1000 kg capacity storage boxes, and placed in a potato storage facility in Meridian, Idaho. Initial sampling for fry color and sugar ends was conducted on Day 1 as outlined in Appendix 4.

Growing degree days was calculated using the following equation:

$GDD = [(T_{MAX} + T_{MIN})/2] – T_{BASE}$

T_{MAX} = Daily maximum, T_{MIN} = Daily minimum, T_{BASE} = Base temperature of $10^{o}C$

Weather data was collected from https://www.wunderground.com/history.

(McMaster & Wilhelm, 1997)

The data from the field study for the parameters of total yield, >170 grams, specific gravity, and calculated data for sugar ends were statistically analyzed using a Split Plot ANOVA.

The statistical analysis for IAP was determined in the following manner: the yield and quality raw data for 2014 and 2015 were averaged across the four replications and the mean was applied to a grower contract with a base price of $7.50/cwt, with appropriate adjustments for specific gravity, > 170 grams, fry color, and sugar ends. (Table 1). The incentive adjusted prices were then statistically analyzed as a Two-Factor without Replication ANOVA to determine the effect of harvest timing on IAP (Table 3).

RESULTS

This study was originally designed to average the grower contract data for 2014 and 2015. However, the growing conditions for the two years were considerably different leading to profound differences in certain parameters of the grower contract that adversely affected IAP. The growing conditions in 2014 were relatively comparable to the 10 year norm for southwest Idaho (Figure 3). However, 2015 had greater temperatures extremes than in 2014 (Table 3 and Figure 3), resulting in lower US No. 1 yields and more symptoms of stressed potatoes.

Growing degree days for the growing seasons of 2014 and 2015 further served to display the differences in temperature extremes. In 2014, the month of June had 273 growing degree days in comparison to 474 in 2015. Cumulative degree days for May through September was 1650 in 2014 and 1882 in 2015 (Table 4)

<u>Physiological Maturity Indexes</u>

Physiological Maturity Indexes for sucrose, glucose, and specific gravity provided additional data to determine the maturity of the potatoes harvested at three different times (Figure 4). In 2014, low sucrose and glucose with high specific gravity indicate that Russet Burbank harvested early may have been closer to physiologically maturity than immaturity. Increasing sucrose levels and declining specific gravity indicate that Russet Burbank was physiologically overly mature at late harvest. Alpine Russet was physiologically immature at early harvest and overly mature at late harvest as shown by an increase in sucrose and decrease in specific gravity over time. Although Clearwater Russet had increasing sucrose and glucose levels over time, Clearwater Russet also had specific gravities that continued to increase over time, indicating that the crop was still immature at late harvest in 2014. In 2015, Russet Burbank had the lowest specific gravity at early harvest and high sucrose levels, indicating that the crop was physiologically immature at early harvest. Russet Burbank was physiologically immature at normal harvest with high sucrose levels and low specific gravities. At late harvest, which was harvested a week earlier than in 2014, Russet Burbank had declining sucrose and increasing specific gravities, indicating that tubers from the late harvest treatment may have been closer to mature than overly mature. As found in 2015, Clearwater Russet had increasing specific gravity over each harvest timing with declining sucrose levels at late harvest, indicating that the crop was physiologically mature at late harvest. Alpine Russet was physiologically immature at early harvest with high sucrose levels and low specific gravities. Decreasing sucrose levels and specific gravity indicate that Alpine tubers from the late harvest treatment were physiologically over mature.

Total Yield

Total yield was significantly influenced by harvest date (Table 5 and Figure 5). Regardless of growing conditions in either year, late harvest had a significantly higher yield than the early and normal harvest treatments. The data also show that 2014 growing season provided higher total yields at each of the three harvest dates than in 2015.

Variety had a significant effect on total yield (Table 5 and Figure 6). Russet Burbank had significantly higher total yield than either Alpine Russet or Clearwater Russet in 2014 and significantly higher total yield than Clearwater Russet in 2015.

Tuber Size Distribution as a percentage of total yield

Harvest timing had a significant influence on tuber size distribution as a percentage of total yield (Table 6 and Figures 7 and 8). In 2014, late harvest produced significantly more tubers in the 284 – 340g and >340g category and normal harvest produced significantly more tubers in the #2's category. In 2015, early harvest produced significantly more tubers in the 115 – 170g category. In the >340g category in 2015, late harvest produced significantly more tubers than normal harvest which produced significantly more tubers than early harvest.

Variety significantly affected all tuber size parameters as a percentage of total yield in both study years (Table 6 and Figures 7 and 8). In 2014, Russet Burbank produced significantly more culls. Clearwater Russet produced significantly more tubers in the <114g, 115 - 170g, and 171 – 283g categories and produced significantly fewer >340g and #2 tubers. Alpine Russet produced significantly more tubers in the 284 - 340g. In 2015, Russet Burbank produced significantly more <114g tubers, #2's, and cull tubers. Alpine Russet produced significantly fewer <114g, 115 – 170g, and 171 – 283g tubers and significantly more 284 – 340 and >340g tubers.

>170g for contract

Late harvest in both 2014 and 2015 produced significantly more tubers in >170g size category than either early harvest or normal harvest. Early harvest produced the least amount of tubers in the >170g size category in both years (Table 5, Figures 9 and 10).

There were considerable differences among varieties with respect to tuber size distribution. In 2014, Alpine Russet and Russet Burbank produced more tubers in the > 170g size category than Clearwater Russet. In 2015, Alpine Russet produced significantly more tubers in the > 170g size category than either Clearwater Russet or Russet Burbank (Table 5, Figures 9 and 10).

Tuber Specific Gravity

Both harvest timing and variety significantly impacted tuber specific gravities (Table 5).

Early harvest had significantly lower tuber specific gravities compared to the other two harvest treatments for both 2014 and 2015 (Figure 11).

Russet Burbank tubers had significantly lower specific gravities than either Clearwater Russet or Alpine Russet tubers in both study years. Alpine Russet had tuber specific gravities that were significantly lower than Clearwater Russet in 2014, but significantly higher than Russet Burbank. In 2015, specific gravities for Alpine Russet tubers were significantly higher than Russet Burbank.

Clearwater Russet tubers had significantly higher specific gravities than either Russet Burbank or Alpine Russet tubers in 2014 and 2015. In addition, specific gravity of Clearwater Russet increased with each harvest timing displaying a significant harvest timing by variety interaction in 2014 that was not noted with Russet Burbank or Alpine Russet (Figure 12).

Comparison of Research to Previous Studies

Previous studies conducted on Clearwater Russet and Alpine Russet (Novy, *et al.,* 2010; Whitworth, *et al.,* 2011) found that both varieties had lower incidence of sugar ends and better fry colors than Russet Burbank. Alpine Russet also had a greater number of >170 grams than Russet Burbank (Whitworth *et al.*, 2011). Clearwater had lower total yield when compared to Russet Burbank with fewer potatoes in the >170g category (Novy *et al.*, 2010). These earlier findings were confirmed with this study. However, Russet Burbank had consistently higher total yield than Alpine Russet, which was in contradiction to earlier reports (Whitworth *et al.*, 2011). Earlier studies indicated that the specific gravity of Clearwater Russet was comparable to Russet Burbank (Novy, *et al*., 2011), however, in this study, Clearwater Russet had consistently higher specific gravities in both study years across all three harvest timings when compared to Russet Burbank.

Incentive- Adjusted Price

Overall, harvest timing contributed to differences in IAP (Table 5 and Figure 13). The major impact of harvest timing on IAP in both years was due to the differences in specific gravity and the percentage of tubers > 170 grams. Tubers harvested in 2015 had a higher number and greater severity of sugar ends with Russet Burbank, which had a substantial and negative impact on IAP (Table 5).

Early harvest in both years produced the lowest IAP, regardless of variety.

Variety had a significant effect on incentive-adjusted price in both years of the study (Table 5). In 2014, Alpine Russet had a significantly higher IAP than Russet Burbank or Clearwater Russet (Figure 14). However, in 2015, IAP was significantly different based on variety with Russet Burbank having significantly lower IAP compared to Clearwater Russet and Alpine Russet.

The basis for these differences in IAP due to harvest timing and variety were as a result of adjustments to the base price due to incentives for specific gravity, size, and incidence of sugar ends as outlined in Tables 7 and 8.

Effect of Early Harvest Incentives

Early Harvest Incentives were inconsistent in offsetting the losses associated with early harvest (Table 9). In 2014, the total quality adjustment for Alpine Russet was positive and therefore the early harvest incentive served to increase the net price and revenue/hectare. Early harvest incentives offset the losses in total quality adjustments incurred by an early harvest with Clearwater Russet, however, due to low yield, the revenue/acre was the lowest of the three varieties. Early harvest incentives did not offset the economic losses with Russet Burbank and there was a decline in net price, however, due to the higher total yield that was applied to the contract, the revenue/acre was acceptable. In 2015, the total quality adjustment for all three varieties resulted in a loss in IAP. The early harvest incentives were insufficient to offset losses with Russet Burbank, even when the higher total yield was applied to the contract. The early harvest incentives compensated for economic losses incurred by an early harvest with Alpine Russet and Clearwater Russet.

DISCUSSION

Choices regarding which variety to plant and when to harvest greatly impacted the IAP and accordingly, the income received by a grower as well as the profit margin for the processor. Additional information on the impact of harvest timing can provide both growers and processors with data that can be financially beneficial. This will enable the grower to potentially secure a profit from his crop while allowing the processor to produce a high quality, profitable product.

The results of this study indicated that both harvest timing and variety influence IAP. The results also showed that the early harvest incentives provided in the grower contract were not consistently sufficient to offset economic losses associated with early harvest. In addition, the differences in growing conditions between 2014 and 2015 provided valuable information on the impact of growing conditions on harvest timing and varietal response and the subsequent effects upon IAP, net price, and revenue per hectare.

Early harvest timing negatively affected the IAP, resulting in potential economic losses for the grower. Early harvest produced lower yields, which affected the total number of tons that were applied to the contract. Early harvest also had lower specific gravities and reduced tuber size, thereby reducing the overall IAP. The effect of early harvest on IAP was even greater during 2015. Potatoes grown in 2015 produced substantially lower total yield, smaller potatoes, and a significantly greater percentage of sugar ends. The combined effects of early harvest and sugar ends reduced IAP and revenue/ha.

An early harvest can also be detrimental to the manufacturing goals of a processor. In addition to a reduction to IAP, crops harvested prior to physiological maturity will have lower specific gravities that will negatively impact the fry and textural quality of end-products, especially French fries. These crops will often fail to meet size requirements critical to producing acceptable French fries. When raw product supply is scarce during the overlap of new crop and old crop potatoes, processors face a trade-off between quality and market timing.

Early harvest incentives designed to balance losses associated with an early harvest did not consistently provide the grower with that advantage. Russet Burbank had a higher total quality adjustment in both study years compared to Clearwater Russet or Alpine Russet. The early harvest adjustment of $0.20 in 2014 and $0.40 in 2015 proved insufficient to compensate for those losses and so the net price of Russet Burbank was lower than the base price in both 2014 and 2015. Early harvest incentives provided in the grower contract were sufficient with Clearwater Russet and Alpine Russet, enabling the grower to exceed base price.

In this study, the late harvest treatment had an additional four weeks of tuber bulking compared to early harvest and an additional two weeks of tuber bulking compared to normal harvest. The advantage of this additional time for bulking was evident in total yield. In both 2014 and 2015, late harvest produced the highest total yield providing the grower with the opportunity to sell a greater volume of potatoes.

Significant varietal differences were also noted. This study revealed that Russet Burbank produced crops with consistently higher total yield in both study years than either Clearwater Russet or Alpine Russet. This higher yield is one reason that growers continue to produce Russet Burbank and processors continue to contract for the variety, regardless of other detrimental agronomic or quality issues. However, Russet Burbank consistently produced tubers with lower specific gravities than Clearwater Russet or Alpine Russet, reducing the IAP. In addition, the higher sugar ends observed with Russet Burbank in 2015 reduced IAP.

Alpine Russet produced tubers with a higher percentage within the >170g size category, increasing the IAP substantially. With higher specific gravities and higher yield and lower sugar ends than Russet Burbank, this variety was more profitable in 2014. In 2015, Alpine Russet tubers were oversized with the late harvest treatment, which reduced the IAP from penalties associated with excessively large potatoes. However, harvesting this variety at normal harvest provided high specific gravities with more appropriate sizing for a better profit.

Clearwater Russet produced crops with significantly higher specific gravities than either Russet Burbank or Alpine Russet, in both study years. In fact, Clearwater Russet produced tubers with high specific gravities during 2015, increasing the IAP when Russet Burbank and Alpine Russet did not. Furthermore, Clearwater Russet also had a low incidence of sugar ends in both 2014 and 2015. Clearwater Russet did not produce potatoes with adequate size with early harvest, indicating that additional time is required in the field for tuber bulking. This study showed that the late harvest allowed Clearwater Russet to acquire desirable processing size and increase the IAP.

Processors should reconsider their position on early harvesting practices, especially if the variety is late maturing. The effect of lower total yield reduced the total number of tons of potatoes to be applied to the contract. In addition, early harvest incurred deductions for inadequate size of potatoes and lower tuber specific gravity, reducing IAP considerably. Processors should also reevaluate the early harvest incentives to ensure that they adequately compensate growers for harvesting early.

In addition, growers and processors in Western Idaho should reevaluate the choice of variety for processing French Fries. The economic analysis of field data indicates that Russet Burbank possesses numerous agronomic issues that are detrimental to the income of potato growers as well as producing lower quality potatoes that reduce overall end-product quality. Alpine Russet consistently reached specific gravity and size requirements with no sugar ends, helping the increase the IAP. This variety can exceed size requirements by late harvest, but harvesting a normal timing would provide the grower with a high value crop that also met the parameters of a grower contract and increase the IAP.

Clearwater Russet requires additional time to reach preferred processing size, but performed well in terms of specific gravity and sugar ends. If allowed to reach physiological maturity with a later harvest, Clearwater Russet has the best potential to maximize the IAP of the three varieties evaluated in this study and increase revenue/hectare. Harvesting at physiological maturity or later would enable farmers to grow high quality product with high specific gravities, low sugar ends, and within the desired >170g size parameters. The combination of these factors would enable the farmer to grow a crop that could provide substantially higher IAP.

CONCLUSIONS

The study was originally designed to evaluate the effects of harvest timing on total yield of three processing varieties as well as tubers of >170 grams, specific gravity, sugar ends, fry color and the resulting effects on IAP. Results from this study showed that a late harvest consistently increased total yield and >170 gram potatoes in both study years, while an early harvest had reduced specific gravities. These results correlated with previous studies (DeBuchananne & Lawson, 1991; Driskill *et al.,* 2007; Kleinschmidt *et al.,* 1984). Harvest timing did affect both total yield and IAP, but it became evident that the effect of variety on IAP was greater.

For several decades, Russet Burbank has been the gold standard for French fry production. With relatively high specific gravities and long dormancy in storage, this variety produced high quality French fries for major processors across the country. However, Russet Burbank is a heat and water-stress sensitive variety and these characteristics lead to undesirable quality issues in the finished product, including sugar ends and darkened fry color. In growing seasons that experience high temperature extremes or drought conditions, early harvest incentives may be inadequate to offset potential economic losses. Russet Burbank remains a favorite with growers due to its higher total yield, but the total quality adjustments for this variety are oftentimes so severe that the higher total yield is negated by quality deductions.

New varieties, such as Clearwater Russet and Alpine Russet are more tolerant of stressful field conditions and more sustainable in terms of water and fertility needs while still providing high yield and adequate sized potatoes for processing. In addition, successful breeding programs have incorporated cold temperature sweetening resistance, disease and pest resistance, improved fry color, and reduced sugar ends into these newer varieties. Therefore, these new varieties have the potential to become incorporated into sustainable farming practices that deal with reduced water availability, higher disease pressure, and climate change.

Overall, the new varieties, Clearwater Russet and Alpine Russet possessed traits that increased IAP. Alpine Russet increased IAP with higher >170g potatoes and reduced sugar ends. Clearwater Russet increased the IAP with significantly higher specific gravities and reduced sugar ends. Furthermore, Clearwater Russet has the potential to reach the desired size parameter of >170g, if allowed to mature and be harvested at a later harvest. This would further increase IAP and potential revenue for the grower.

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Table 1. Example of a hypothetical Russet Burbank grower contract incentives. A base price of $165 USD/ton was applied for research purposes, to which the appropriate incentives were added or subtracted to determine the incentive adjusted price.

>170 grams	
Per % below	-$.66
45%	-$9.92
46%	-$9.26
47%	-$8.60
48%	-$7.94
49%	-$7.28
50%	-$6.62
51%	-$5.95
52%	-$5.29
53%	-$4.63
54%	-$3.97
55%	-$3.31
56%	-$2.65
57%	-$1.98
58%	-$1.32
59%	-$0.66
60%	$0.00
61%	$0.66
62%	$1.32
63%	$1.98
64%	$2.65
65%	$3.31
66%	$3.97
67%	$4.63
68%	$5.29
69%	$5.95
70%	$6.62
71%	$7.28
72%	$7.28
73%	$7.28
74%	$7.28
75%	$7.28
76%	$7.28
77%	$7.28
78%	$7.28
79%	$7.28
80%	$7.28
81%	$6.62

>170 grams (cont.)	
82%	$5.29
83%	$4.63
84%	$3.97
Per % above	-$.66
Specific Gravity	
Per 0.001 below	-$2.20
1.069	-$13.67
1.070	-$11.47
1.071	-$9.26
1.072	-$7.06
1.073	-$4.85
1.074	-$2.65
1.075	-$1.98
1.076	-$1.32
1.077	-$0.66
1.078	$0.00
1.079	$0.66
1.080	$1.32
1.081	$1.98
1.082	$2.65
1.083	$3.30
1.084	$3.97
1.085	$4.63
1.086	$4.63
1.087	$4.63
1.088	$3.97
1.089	$3.97
1.090	$3.97
1.091	$3.97
1.092	$3.97
1.093	$0.18
1.094	$0.15
1.095	$0.12
1.096	$0.12
1.097	$0.12
1.098	$0.12
1.099	$0.12
1.100	$0.12

Sugar Ends	
0%	$0.00
1%	$0.00
2%	$0.00
3%	$0.00
4%	$0.00
5%	$0.00
6%	$0.00
7%	$0.00
8%	$0.00
9%	-$1.10
10%	-$2.20
11%	-$3.30
12%	-$4.40
13%	-$5.51
14%	-$6.62
15%	-$7.72
16%	-$8.82
17%	-$9.92
18%	-$11.02
19%	-$12.13
20%	-$13.23
per % above	-$1.10

Fry Color	
0 Color %	$0.022
1 Color %	$0.000
2 Color %	-$0.022
3 Color %	-$0.110
4 Color %	-$0.110

Table 2. Planting, vine kill, harvest, and days after planting for potatoes grown in Parma, ID during 2014 and 2015.

	2014			2015		
	Early	Normal	Late	Early	Normal	Late
Planting Day	15-April-14	15-April-14	15-April-14	15-April-15	15-April-15	15-April-15
Vine Kill	14-Aug-14	28-Aug-14	11-Sep-14	13-Aug-15	24-Aug-15	8-Sep-15
Days after Planting	121	135	149	120	131	146
Harvest	28-Aug-14	11-Sep-14	28-Sep-14	24-Aug-15	8-Sep-15	21-Sep-15
Days after Planting	135	149	166	131	146	159

Early = Early harvest, Normal = Normal harvest, Late = Late harvest

Table 3. Monthly means for daily minimum, maximum, and mean temperatures in Parma, Idaho in 2014 and 2015.

Month	Min Temp °C		Max Temp °C		Mean Temp °C	
	2014	2015	2014	2015	2014	2015
May	10.0	12.7	21.6	23.3	16.6	17.2
June	12.7	17.7	25.5	33.8	20.5	25.0
July	20.5	17.2	32.7	32.2	27.2	25.0
August	17.7	19.4	28.3	29.4	23.8	24.4
September	13.8	12.7	24.4	24.4	19.4	17.7

Temperatures for Parma, Idaho in 2014 and 2015 were obtained from https://www.wunderground.com/history

Table 4. Growing Degree-days for growing seasons in Parma, Idaho in 2014 and 2015.

Month	Growing Degree-Days	
	2014	2015
May	186	248
June	273	474
July	515	456
August	403	446
September	273	258
Cumulative Degree-Days	1650	1882

Equation for Growing Degree-days acquired from McMaster and Wilhelm, 1997.
Temperatures for Parma, Idaho in 2014 and 2015 were obtained from https://www.wunderground.com/history

Table 5. Analysis of variance for effect of harvest timing and variety on total yield, >170g, specific gravity, sugar ends, and incentive adjusted price for potatoes grown at Parma, ID during 2014 and 2015.

		F-value																			
Source	**DF**	**Total Yield**				**>170 grams**				**Specific Gravity**				**Sugar Ends**				**IAP**			
		2014		**2015**		**2014**		**2015**		**2014**		**2015**		**2014**		**2015**		**2014**		**2015**	
Repetition	**3**	**1.10**	**ns**	**4.73**	**ns**	**1.05**	**ns**	**1.49**	**ns**	**1.54**	**ns**	**1.39**	**ns**	**0.58**	**ns**	**0.86**	**ns**	**n/a**	**n/a**	**n/a**	**n/a**
Variety	**2**	**2.33**	*****	**7.29**	*****	**15.87**	*****	**18.00**	*****	**29.50**	*****	**11.42**	*****	**6.54**	*****	**42.50**	*****	**3.10**	*****	**74.80**	*****
Repetition x Variety	**6**	**0.12**	**ns**	**1.03**	**ns**	**0.38**	**ns**	**1.01**	**ns**	**0.30**	**ns**	**1.21**	**ns**	**1.21**	**ns**	**1.24**	**ns**	**n/a**	**n/a**	**n/a**	**n/a**
Timing	**2**	**10.6**	*****	**8.25**	*****	**10.42**	*****	**8.21**	*****	**4.44**	*****	**3.23**	*****	**10.96**	*****	**7.82**	*****	**4.10**	*****	**3.20**	*****
Variety x Timing	**4**	**0.66**	**ns**	**1.18**	**ns**	**0.50**	**ns**	**1.44**	**ns**	**3.25**	*****	**3.19**	*****	**6.54**	*****	**0.93**	**ns**	**0.60**	**ns**	**0.50**	**ns**

IAP = Incentive Adjusted Price – calculated by applying data from >170 grams, tuber specific gravity, and sugar ends to the parameters of a grower contract. * denotes significance, ns = not significant, $p < 0.05$. n/a = not applicable

Table 6. Yield, tuber size distribution as percent of total yield, and F-values for three processing varieties; Russet Burbank, Clearwater Russet, and Alpine Russet, at three different harvest timings; early, normal, and late.

	Yield (t/ha)						Tuber Size Distribution as Percent of Total Yield													
Main Effect	Total		U.S. No. 1		% No. 1		<114 grams		115 to 170 g		171 to 283 g		284 to 340 g		>340 grams		#2's		Cull	
	2014	2015	2014	2015	2014	2015	2014	2015	2014	2015	2014	2015	2014	2015	2014	2015	2014	2015	2014	2015
Variety [1]																				
Russet Burbank	81.3a	70.1a	60.3a	45.7b	84.4b	74.8c	11.4b	15.8a	16.3b	18.3a	31.2b	32.4a	12.1ab	9.9b	24.9a	14.3c	1.6a	3.7a	2.9a	6.1a
Clearwater Russet	73.4b	61.5b	53.6b	47.5b	82.9b	87.9b	16.0a	9.6b	28.6a	19.3a	38.3a	36.8a	10.0b	10.6b	6.3b	21.2b	0.5b	0.9b	0.4b	1.4b
Alpine Russet	76.4b	64.7b	60.3a	53.5a	90.1a	93.8a	8.5c	3.6c	15.8b	6.9b	31.5b	23.7b	23.7a	15.9a	27.3a	47.3a	1.4a	0.9b	0.2b	1.8b
Harvest Timing [1]																				
Early	72.8b	62.0b	54.3b	45.7b	85.1a	84.5a	12.2a	11.0a	20.0a	19.7a	32.9b	31.7a	12.5b	11.0a	18.5b	22.3c	0.2a	2.1a	1.4a	2.9a
Normal	71.5b	63.6b	54.0b	47.8b	85.8a	85.9a	13.1a	9.8a	22.5a	13.2b	33.6a	31.2a	12.0b	13.7a	18.1b	27.9b	1.4b	1.8a	0.9a	2.8a
Late	86.8a	70.6a	65.8a	53.2a	86.4a	86.2a	11.0a	8.2a	18.1a	11.6b	33.3b	30.3a	13.1a	11.9a	22.0a	32.6a	0.6a	2.0a	1.1a	3.6a
F-Values																				
Variety (V)	2.3*	7.2*	8.4*	7.8*	8.3*	7.6*	37*	59.0*	40.5*	45.0*	5.4*	23.0*	6.4*	9.2*	56.0*	33.5*	3.2*	14.0*	18.5*	14.0*
Harvest Timing (T)	10.6*	8.2*	6.8*	5.4*	1.4^{ns}	2.6^{ns}	2.0^{ns}	0.7^{ns}	1.2^{ns}	9.8*	7.9*	1.2^{ns}	2.9*	2.4^{ns}	7.2*	5.3*	10.4*	0.8^{ns}	1.5^{ns}	0.6^{ns}
VxT	0.6^{ns}	1.1^{ns}	9.6*	10.3*	3.4^{ns}	3.7^{ns}	0.4^{ns}	0.2^{ns}	0.2^{ns}	1.6^{ns}	2.8^{ns}	3.4*	0.9^{ns}	1.6^{ns}	1.2^{ns}	0.8^{ns}	5.4*	1.6^{ns}	0.3^{ns}	0.9^{ns}

t/ha = ton/hectare, g=grams, Means within a year with same letter are not significantly different at $p < 0.05$. *denotes significance, ns = not significant

Table 7. Effect of harvest timing on incentive adjustments to the base contract price averaged across three varieties in 2014 and 2015.

	Adjust to the base price ($/ton)								
	Specific Gravity			>170 grams			Sugar Ends		
	Early	Normal	Late	Early	Normal	Late	Early	Normal	Late
2014	**-$2.65**	$2.65	$6.62	$0.15	$3.31	$4.85	**-$2.87**	**-$0.44**	$0.00
2015	**-$18.74**	$3.53	$1.76	**-$0.11**	$2.21	$2.65	**-$7.06**	**-$8.38**	**-$15.44**

Losses are noted in bold

Table 8. Effect of variety on incentive adjustments to the contract price for potatoes grown at Parma, ID during 2014 and 2015. Values are means of three harvest timings.

	Adjustments to base price ($/ton)								
	Specific Gravity			>170 grams			Sugar Ends		
	RB	CR	AR	RB	CR	AR	RB	CR	AR
2014	**-$2.20**	$3.31	**$-0.88**	$6.62	**$-9.92**	$7.28	**$-3.31**	$0.00	$0.00
2015	**-$12.13**	$3.31	**$-0.88**	$1.32	$3.75	$1.32	**$-30.87**	$0.00	$0.00

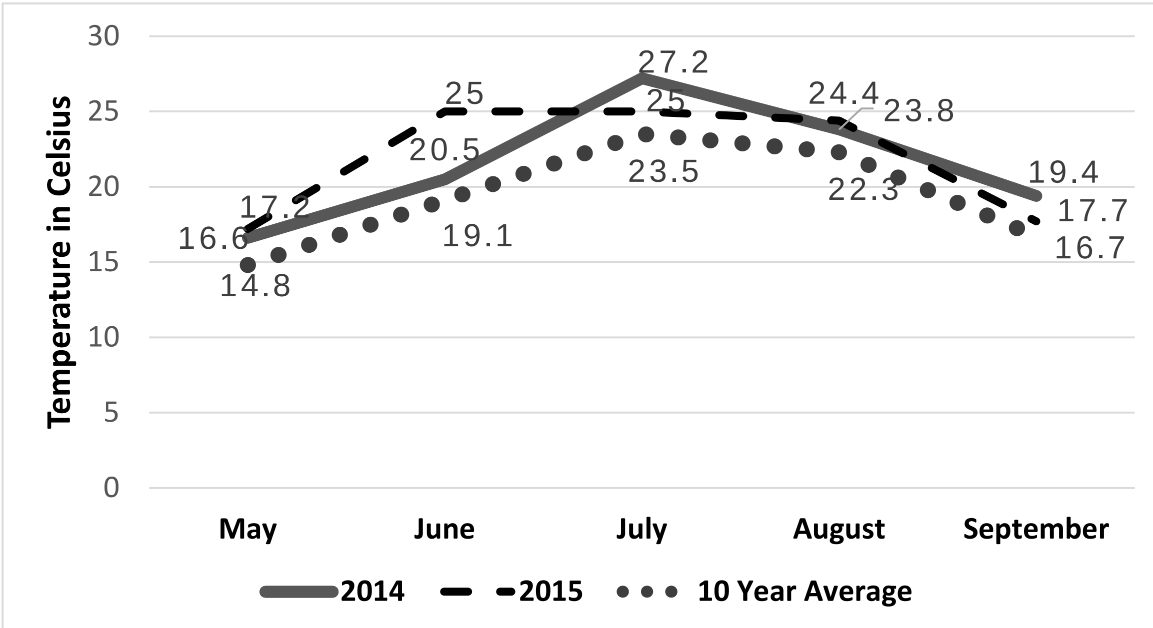
Losses are noted in bold

RB = Russet Burbank, CR = Clearwater Russet, AR = Alpine Russet

Table 9. Effect of early harvest adjustment on net price and revenue/ha in 2014 and 2015 on three processing varieties.

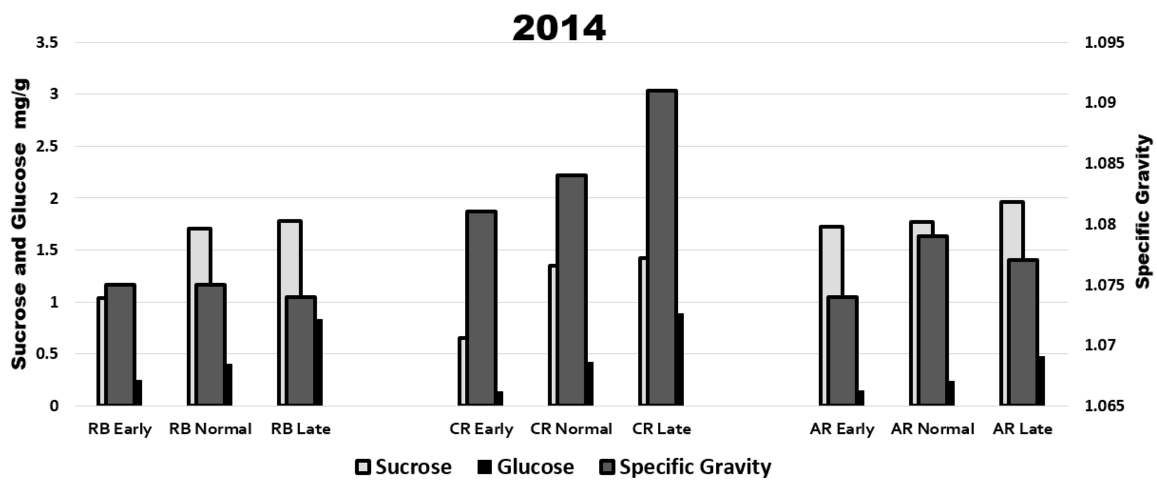
Year	Variety	Total Quality Adjustment	Early Harvest Adjustment	Net Price	Yield ton/ha	Revenue/ha
2014	Russet Burbank	-$4.84	$4.40	$164	66	$10,809
	Clearwater Russet	-$1.32	$4.40	$168	60	$10,093
	Alpine Russet	$4.62	$4.40	$174	66	$11,468
2015	Russet Burbank	-$41.58	$8.80	$132	63	$8,286
	Clearwater Russet	-$1.32	$8.80	$172	52	$8,887
	Alpine Russet	-$3.96	$8.80	$170	56	$9,603

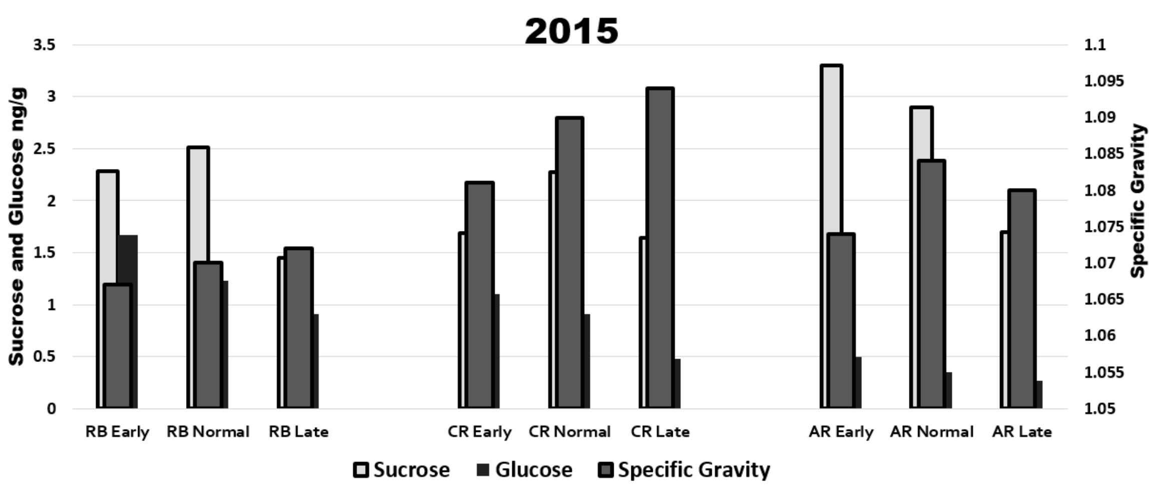
Figure 3. Monthly mean temperatures for Parma, Idaho in 2014 and 2015.



Temperatures for Parma, Idaho in 2014 and 2015 were obtained from https://wunderground.com/history.

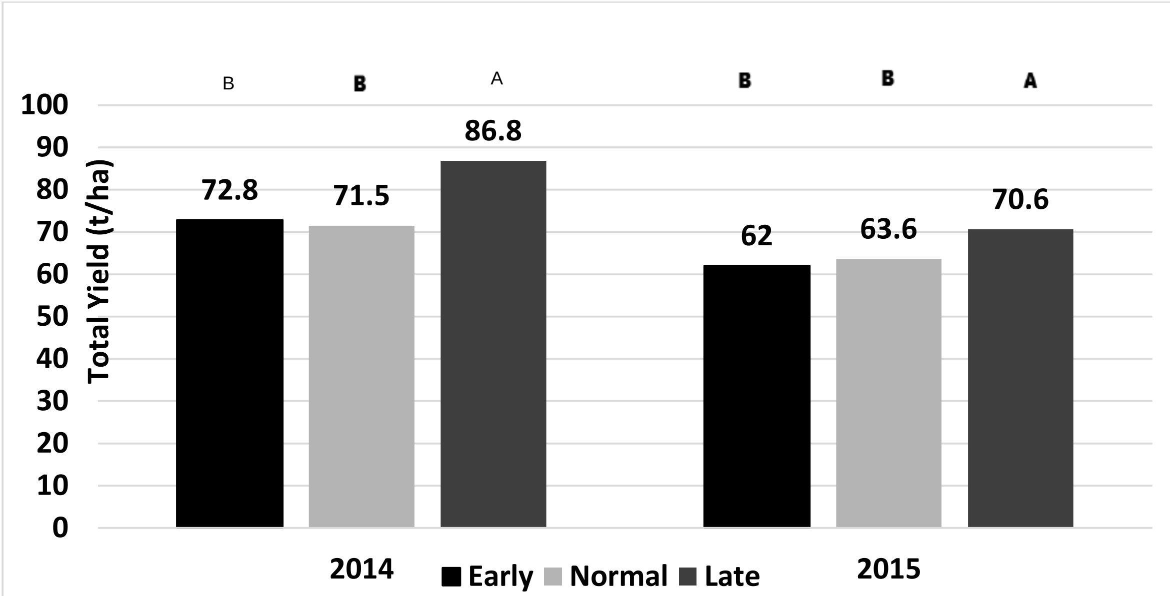
Figure 4. Physiological Maturity Indexes of sucrose, glucose, and specific gravity of Russet Burbank, Clearwater Russet, and Alpine Russet at three harvest timings; early, normal, and late in 2014 and 2015.





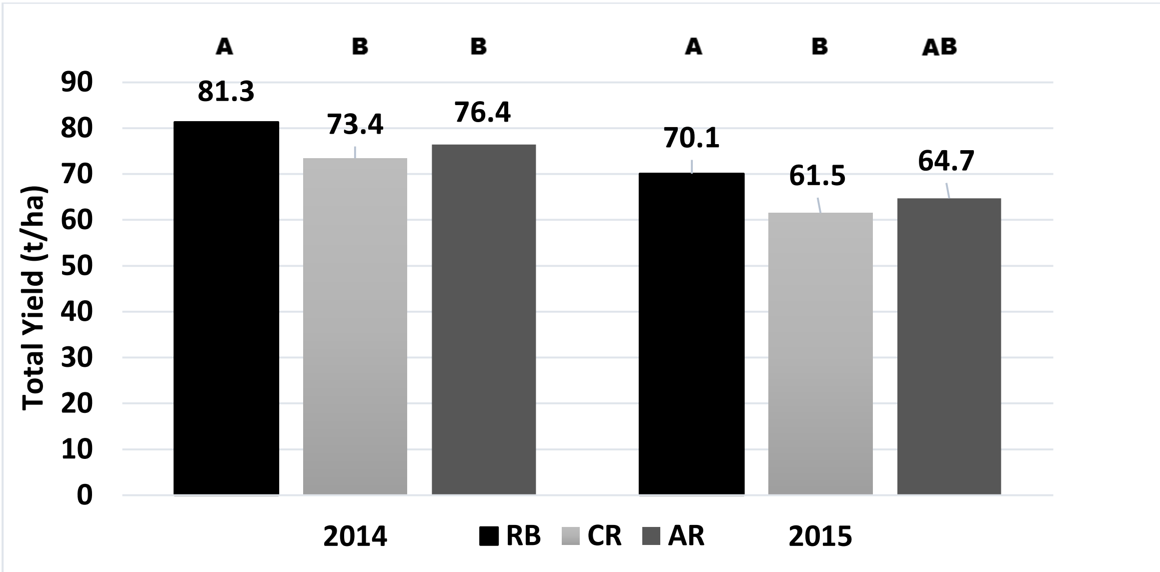
RB=Russet Burbank, CR=Clearwater Russet, AR=Alpine Russet
Potatoes were grown in Parma, Idaho
Early = Early harvest, Normal = Normal harvest, Late = Late harvest

Figure 5. Main effects of harvest timing on total yield during 2014 and 2015. Values are means of 4 replications averaged over three potato varieties.



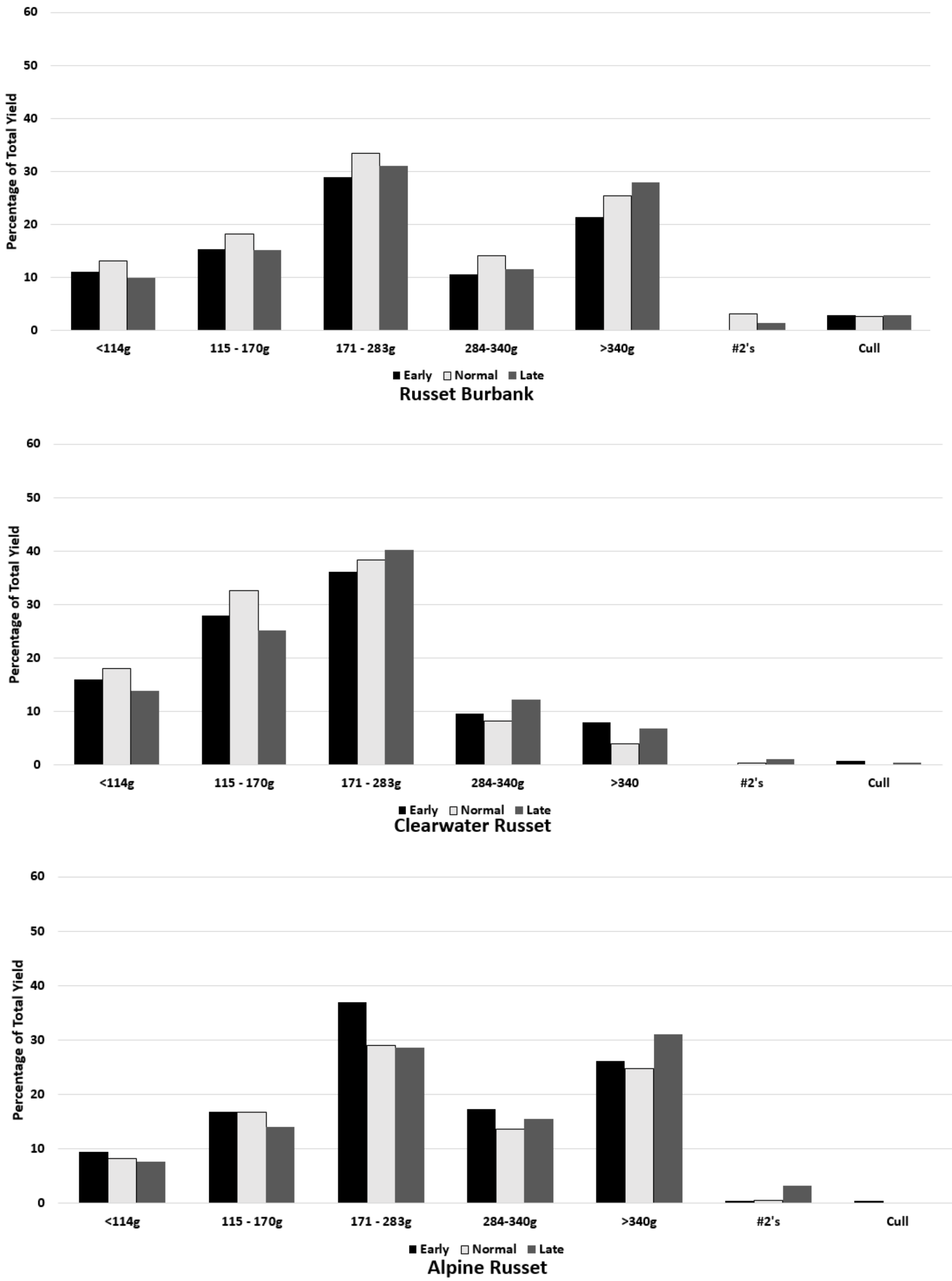
Means within a year with same letter are not significantly different at $p < 0.05$.
Early = Early harvest, Normal = Normal harvest, Late = Late harvest

Figure 6. Main effects of variety on total yield during 2014 and 2015. Values are means of 4 replications averaged across three harvest timings.



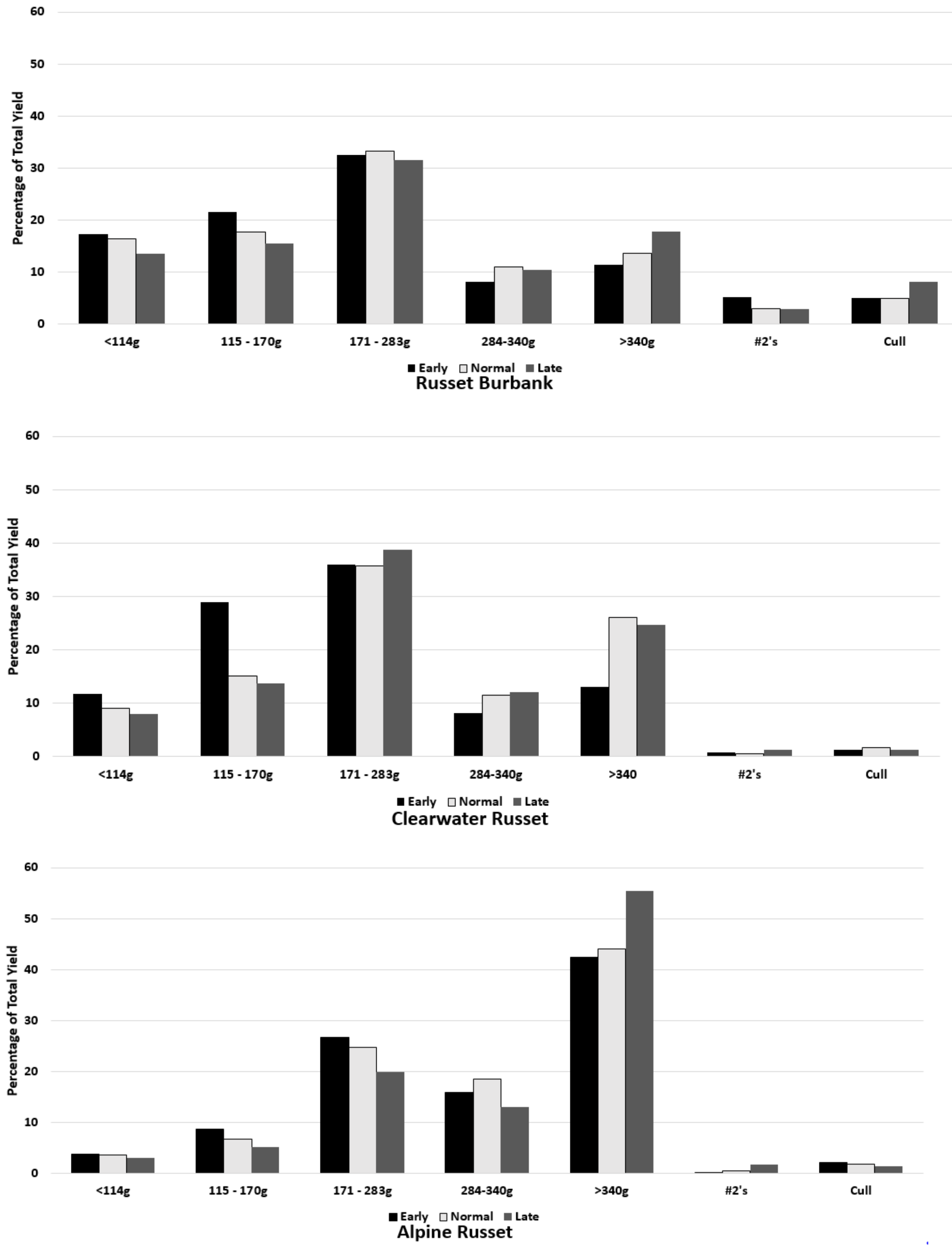
Russet Burbank = RB, Clearwater Russet = CR, and Alpine Russet = AR
Means within a year with same letter for a given year are not significantly different at $p < 0.05$.

Figure 7. Tuber size distribution from three harvest timings, early, normal, and late, as percent of total yield of Russet Burbank, Clearwater Russet, and Alpine Russet in 2014.



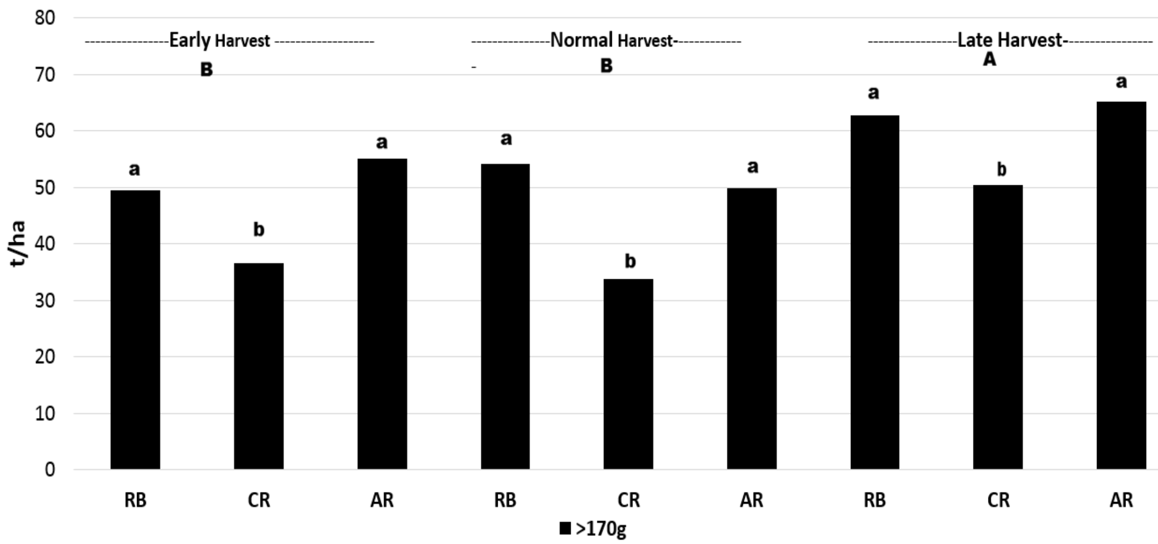
Early = Early harvest, Normal = Normal harvest, Late = Late harvest

Figure 8. Tuber size distribution from three different harvest timing, early, normal, and late, as percent of total yield of Russet Burbank, Clearwater Russet, and Alpine Russet in 2015.



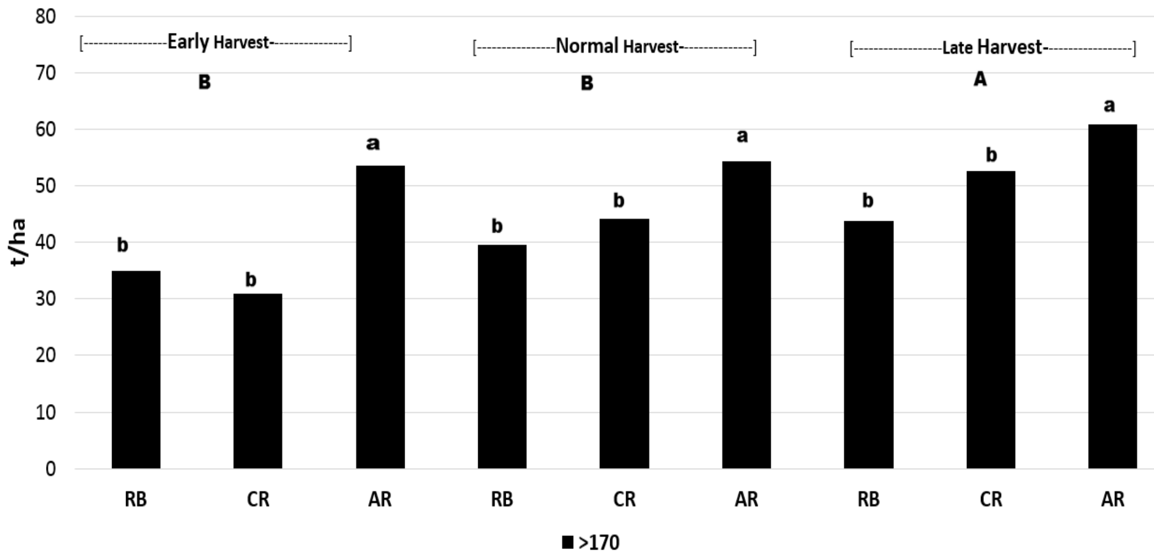
Early = Early harvest, Normal = Normal harvest, Late = Late harvest

Figure 9. Yield of tubers > 170 grams of three potato varieties as influenced by harvest timing in 2014.



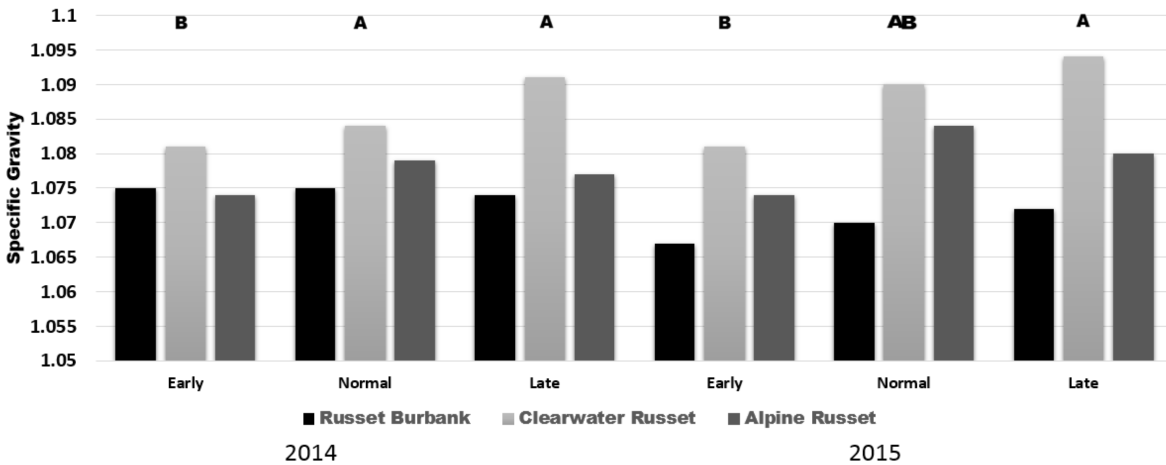
Russet Burbank = RB, Clearwater Russet = CR, and Alpine Russet = AR
Means with same letter are not significantly different at $p < 0.05$.
Capitalized letters refer to harvest timing.
Lower case letters refer to variety.

Figure 10. Yield of tubers > 170 grams of three potato varieties as influenced by harvest timing in 2015.



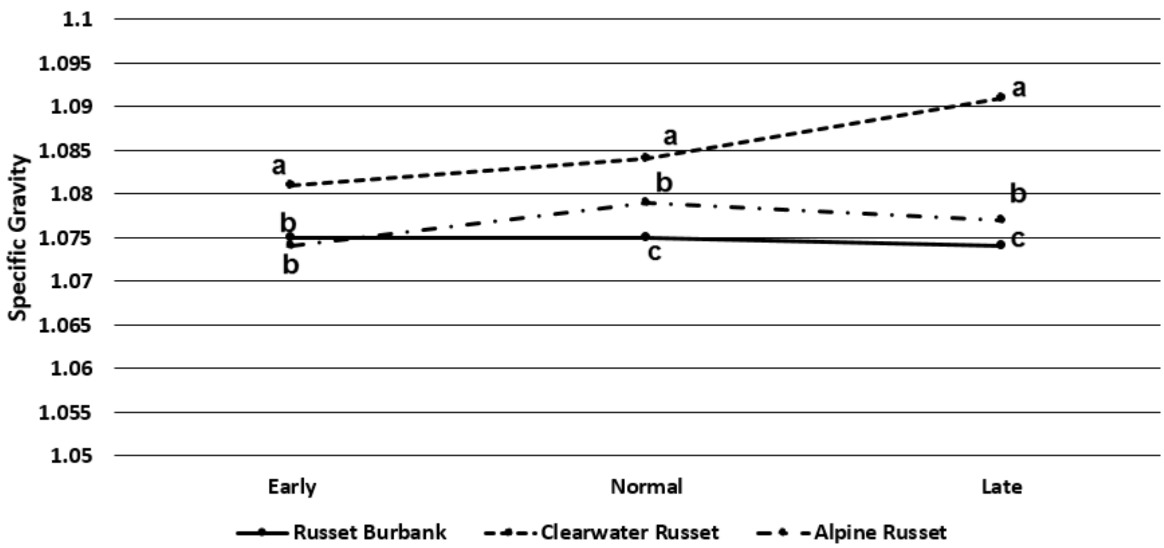
Russet Burbank = RB, Clearwater Russet = CR, and Alpine Russet = AR
Means with same letter are not significantly different at $p < 0.05$.
Capitalized letters refer to harvest timing.
Lower case letters refer to variety.

Figure 11. Tuber specific gravity of three potato varieties as influenced by three harvest timings in 2014 and 2015. Values are means of four replications.



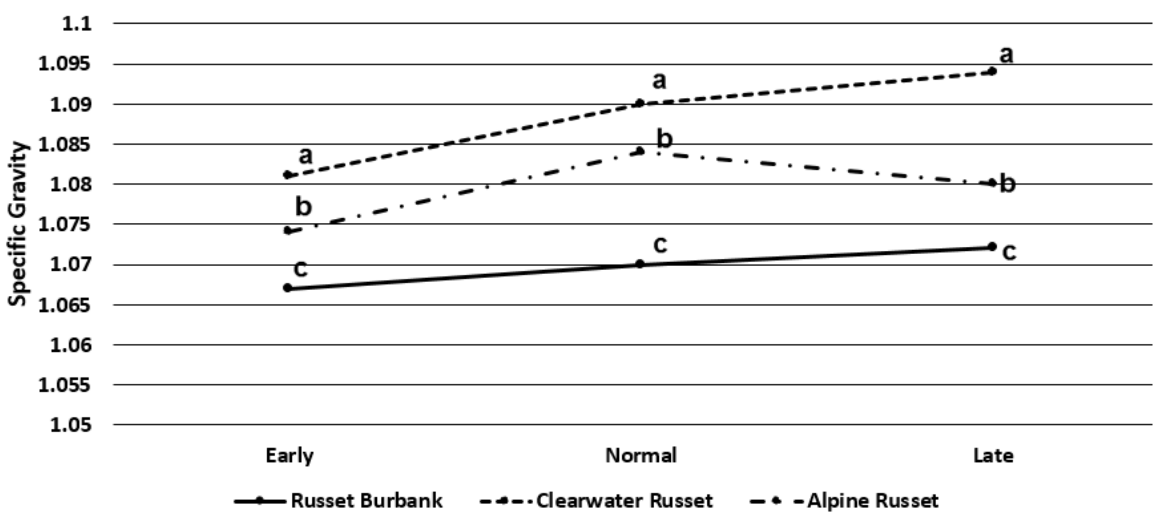
Means with same letter are not significantly different at $p < 0.05$. Early = Early harvest, Normal = Normal harvest, Late = Late harvest

Figure 12. Harvest timing by variety interaction of specific gravity of three processing varieties grown in Parma, Idaho in 2014 and 2015.



2014

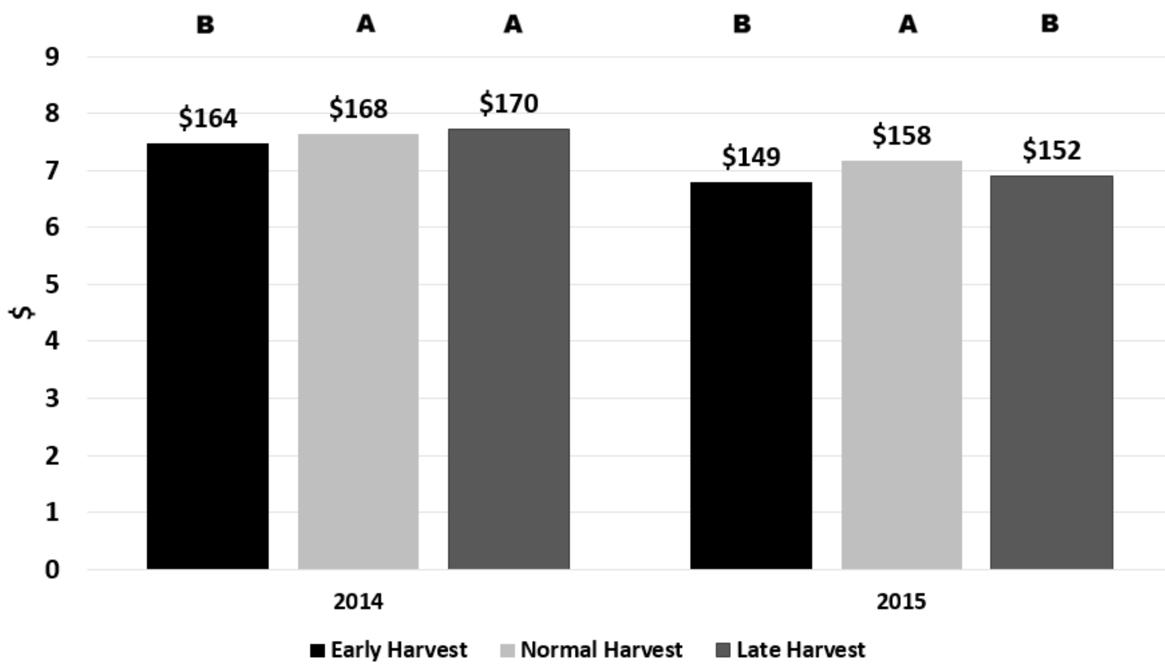
Means within a year with same letter are not significantly different at $p < 0.05$.



2015

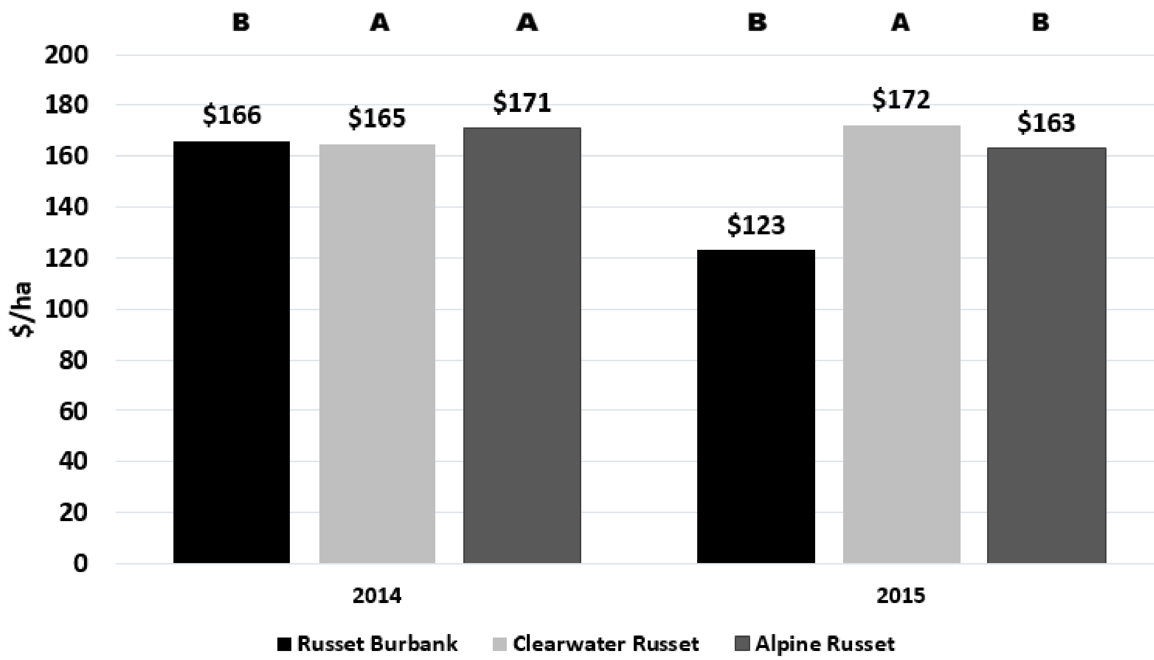
Means within a year with same letter are not significantly different at $p < 0.05$.

Figure 13. Main effects of harvest timing on the incentive-adjusted price of potatoes grown in Parma, ID during 2014 and 2015. Values are means of three potato varieties. Base price = $165/ha.



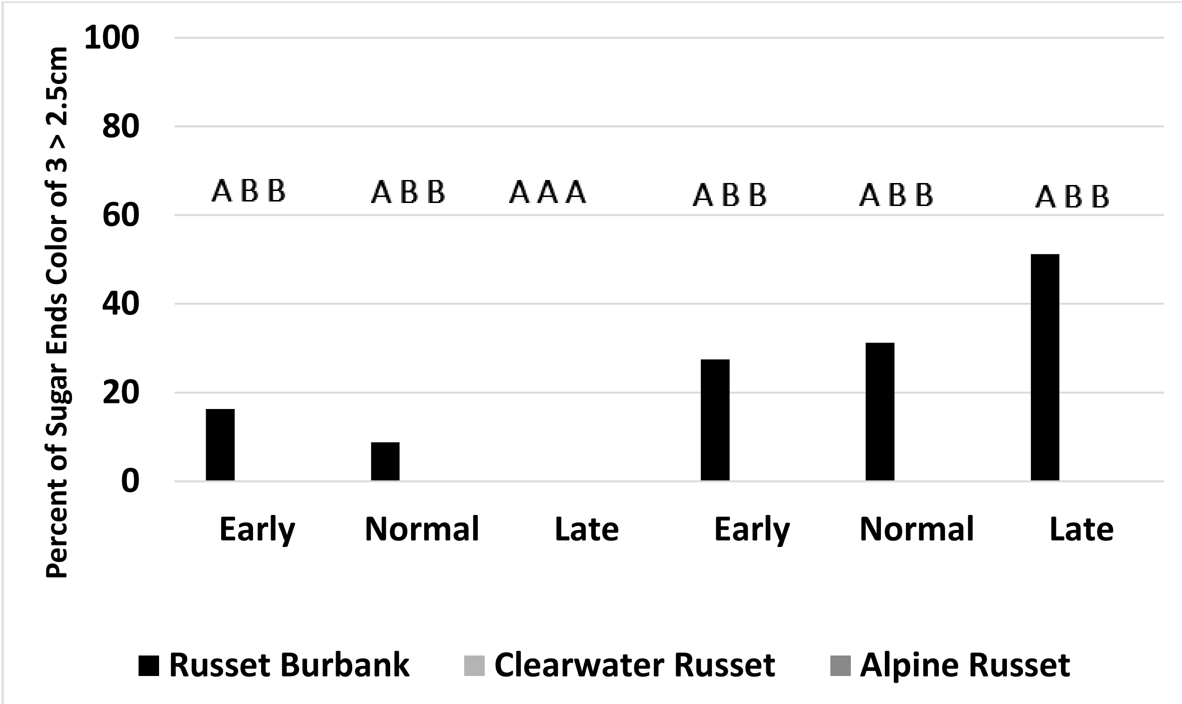
Means within a year with same letter are not significantly different at $p < 0.05$.

Figure 14. Main effects of variety on the incentive adjusted price for potatoes grown in Parma, ID during 2014 and 2015. Values are means of 3 harvest timings. Base price =$165/ha.



Means within a year with same letter for a given year are not significantly different at $p < 0.05$.

Figure 15. Percentage of sugar ends of three processing varieties, across three harvest timings in 2014 and 2015.



Means with the same letter are not significantly different at $p < 0.05$

CHAPTER 3: THE EFFECT OF HARVEST TIMING ON FRENCH FRY TEXTURAL QUALITY OF THREE PROCESSING POTATO VARIETIES

ABSTRACT

This study evaluated the effects of three different harvest dates; early, normal, and late, on quality attributes of French fries produced from three processing varieties, Russet Burbank, Clearwater Russet, and Alpine Russet over a nine month storage season at 8.3^{o}C. Quality attributes evaluated included crispness, external shell, mealiness, and moistness. Fry color, glucose and sucrose content, and sprouting level over time were analyzed concurrently for additional insight into end-product quality over a nine month storage season. Harvest timing impacts on polyphenol oxidase content was examined to determine impact upon graying of French fries. Results of this study show that early harvest is detrimental to producing high quality French fries with regard to texture, and most notably, crispness. During storage, early-harvest French fries declined in quality and were out of grade for crispness at five months after harvest in 2014 and were out of grade at harvest for the full storage season in 2015. Significant differences were noted among the three varieties with regard to texture quality. Clearwater Russet consistently maintained high quality product throughout the storage season. Alpine Russet declined in textural quality five months after harvest. Russet Burbank declined rapidly in textural quality over the course of the storage season, with textural quality becoming unacceptable as early as at harvest. Fry quality was generally acceptable for fry color, incidence of sugar ends, and mottling throughout the full storage season for all varieties and harvest timing treatments. However, Russet Burbank was significantly darker in fry color than either Clearwater Russet or Alpine Russet. In 2015, Russet Burbank had a higher incidence of sugar ends. Differences in mottling were insignificant. Early harvest had a negative impact upon the texture of French fries, particularly crispness. Clearwater Russet maintained acceptable quality with the highest textural scores of all seven parameters for a full nine month storage season.

INTRODUCTION

The enjoyment of consuming our food is largely affected by texture (Sekuler, 2004). Consumers have high expectations about the texture of their foods and if a food product is below their quality standards for texture, the experience for them can be very negative (Rossell, 2001). Due to the globalization of fast food, French fries now have a worldwide appeal, but at the same time, French fries have high quality standards with a narrow window of textural acceptability (Miranda & Aguilera, 2006). Given the international consumption of French fries, it is unexpected that the textural analysis of French fries lacks industry-wide acceptance of standardized measurement methods (Sekuler, 2004). This is due to the human sensation of mouthfeel that is so variable that attempts to use various mechanical instruments or devices to quantify textural characteristics have been unsuccessful. (Du Pont *et al.,* 2007).

Although harvest timing is known to affect the overall texture of French fries, little work has been conducted to evaluate the effect of harvest timing on the specific attributes of textural quality. Therefore, the effect of harvest timing and subsequent storage on the textural characteristics of crispness, exterior shell, mealiness, moistness, texture variation, texture defects, and internal appearance were evaluated using a trained taste panel.

POTENTIAL FACTORS AFFECTING TEXTURE OF FRENCH FRIES AND THE RELATIONSHIP TO HARVEST TIMING

Specific Gravity

Potatoes with a high specific gravity produce French fries with a desirable crispy outer shell with lightly firm exterior shell, a fluffy, light interior with a pleasing level of moistness (Miranda & Aguilera, 2006). French fries produced from potatoes of high specific gravity will have a cooked internal appearance with a slightly hollowing from the edges of the fry (Golubowska, 2005). However, French fries produced with potatoes with low specific gravity will have a weak exterior shell lacking crispness, will not have the acceptable level of mealiness, and the interior of the fry will be raw-looking with no degree of hollowing (Rossell, 2001). French fries with excessively high specific gravity will have a tough exterior shell, dry mouthfeel, and a hollowed-out appearance (Golubowska, 2005).

Starch Composition

The molecular structure of potato starch is a large, smooth granular shape, varying in size from 10 to 100 micro millimeters (Singh & Kaur, 2009). Amylopectin, a highly branched macromolecule, is the key component of potato starch, constituting 70 to 80% by weight (Singh & Kaur, 2009). Amylose is the other building block and is a much smaller molecule than amylopectin and is linear in shape. The highly organized and dense structure of potato starch renders it less likely to succumb to enzymatic degradation (Noda *et al.,* 2004). This structural component allows potatoes to be cooked in a variety of ways while maintaining its desired structural integrity as an end-product (Liu *et al.,* 2003).

Harvest timing can negatively impact the size of the potato granule, which can reduce end-product quality. Generally, large starch granules are preferred for processing due to their greater capacity to swell when cooked, removing free moisture from the flesh of the potato (Singh & Kaur, 2009). Harvesting too early can produce potatoes with smaller starch granules, which are unable to absorb water within the cell (Noda *et al*., 2004). Instead, the water remains outside of the cell and the end-product becomes overly moist (Miranda & Aguilera, 2006). With too much free moisture, French fries lack crispness, the exterior shell lacks structural integrity, and the mealiness may be too smooth (Lisinska & Golubowska, 2005). The overall moistness of the fry will be too high and the visual appearance will portray a raw, uncooked product (Rossell, 2001).

The integrity of the pectic substances of the potato are also important for French fry textural quality (Liu *et al.,* 2003). Studies have shown that potatoes harvested prior to physiological maturity produce potatoes with weaker cross linkages of the branched amylose pectins, resulting in a higher percentage of broken linkages during frying (Jaswal, 1969). The lack of structural integrity substantially weakens the cell wall and results in French fries with poor texture (Liu *et al.,* 2003).

Non-Starch Polysaccharides and Phenolic Polymers

Studies have shown that potatoes of similar specific gravity exhibit varying levels of textural acceptability (Kita, 2002) indicating that specific gravity alone is not the only defining factor influencing textural quality (Lisinska and Golubowska, 2005). Other components of the potato can alter textural quality significantly, including the non-starch polysaccharides (NSP) which include cellulose and pectins, and a phenolic polymer known as lignin (Kita, 2002).

Cellulose is a major component of the plant cell wall, conveying strength and rigidity to the tri-layered cell wall (Fennema, 1996). Cellulose interacts highly with lignin, a phenolic polymer which produces secondary thickening and additional reinforcement of the cell wall (Fennema, 1996). Pectins form the adhesive known as the middle lamella, which holds adjacent cells together, providing further stability to the cellular matrix (Fennema, 1996).

The structural integrity of NSP and lignins are highly important for French fry textural quality (Liu, *et al.,* 2003). Maturity at harvest further affects the relative proportions and contents of the cell wall constituents (Fennema, 1996). Poorly structured cell walls as well as the lack of structural integrity of the middle lamella substantially weaken the cellular matrix, which may experience disintegration during processing, producing French fries with poor interior texture (Liu *et al.,* 2003).

Potato Tuber Size

Harvesting processing varieties at physiological maturity normally provides potatoes of a desired size to meet French fry size parameters (Narasimhamoorthy, *et al.,* 2013). Harvesting early can result in potatoes that are undersized, producing shorter than desired French fries (Narasimhamoorthy *et al.*, 2013). Shorter French fries often have a higher crunch score due to over cooking in the pre-set timed fryers found in the retail quick service restaurants (Rossell, 2001). Excessively large French fries, commonly associated with potatoes from late harvest, are known to produce limp, under cooked fries due to insufficient blanching and decreased oil circulation during the final fry (Sahin et al., 1999).

OBJECTIVES OF STUDY

The objectives of this study are to determine the effect of harvest timing on the textural attributes of crispness, exterior shell, mealiness, moistness, texture variation, texture defects, and internal appearance of three processing varieties, Russet Burbank, Alpine Russet, and Clearwater Russet. Additional objectives include determining the effect of harvest timing on fry color, mottling, sprouting index, and sucrose and glucose concentrations.

MATERIALS AND METHODS

The field portion of this experiment was conducted in 2014 and 2015 at the University of Idaho Research and Extension Center at Parma, Idaho on Greenleaf silt loam soil. The experimental design and cultural management were as outlined in Chapter 2.

The tubers were lifted using a wind rower and then hand harvested into color coded and labeled 25 kg pound mesh bags, weighed and placed into 1000 kg capacity storage boxes, which were placed in a potato storage facility in Meridian, Idaho. Initial sampling for fry color, mottling, sugar ends, sucrose, glucose, and sprout index was conducted within 24 hours of harvest. The tubers were held at 13^{o}C and 95% relative humidity for two weeks for wound healing. The temperature was gradually reduced by approximately 0.35^{o}C per day to reach 8C over 2 weeks. Monthly sampling for fry color began at 1 month after harvest and continued thereafter until 9 months after harvest.

At 1 month after harvest, all tubers received an 8 ppm Chlorpropham (CIPC) treatment, (commercially known as PIN NIP and produced by 1,4GROUP, Meridian, Idaho) via hot fogging at 304^{o}C. At 1 week after treatment, a CIPC residue sample of each replication was taken by sampling 4 tubers from each replication and monthly thereafter (Appendix 3). The tubers were sent to DiChlor Laboratories in Meridian, Idaho for CIPC residue analysis. In 2015, an additional CIPC treatment was required on March 11, 2016 and the chemical was applied at 8ppm (Appendix 3).

The taste panel used for this study was created in accordance with the evaluation standards as set by McDonald's and J. R. Simplot. To acquire a fair assessment of the samples for this study, candidates from the community who met the stringent requirements of the taste panel program were utilized for the bi-monthly taste panels for the two year study (Stone et al., 2012). A total of 42 candidates were interviewed and evaluated. Candidates were first asked if they consumed French fries and if they found consuming French fries enjoyable. A candidate was not selected if French fries were undesirable to that person. Candidates were then asked to discern textural differences among common food items, such as the hardness of crackers to the softness of baloney, the mealiness of mashed potatoes to the smoothness of pudding, and the moistness of fresh cake to the dryness of toast (Stone et al., 2012). Only four of the original 42 candidates met the requirements for discerning subtle differences in textural quality of French fries for all 7 parameters. The four candidates became sensory panelists and were trained to evaluate crispness, exterior shell, mealiness, moistness, texture variation, texture defects, and internal appearance according to a texture profile that was created for each parameter (Figure 16 and Stone et al., 2012 with modifications).

Training to become a taste panelist was conducted at a retail franchise restaurant in Meridian, Idaho between 11 am to noon. An order for 6 extra-large French fries was placed at the counter and timed. Orders taking longer than six minutes were not acceptable for taste panel training (Miranda & Aguilera, 2006). Orders received within 2 to 5 minutes were acceptable for training. The fries were taken to a table and all six orders were poured onto the tray. The trainer began first with the training for crispness by creating 9 labeled piles, 1 – 9, correlating to Figure 16; from a score of 1, which was less crisp and unacceptable, to a 5, which was perfect crispness and acceptable, to a 9, which was crunchy and unacceptable. The panelists tasted fries within each of the nine piles to acquaint themselves with that textural score. This process was repeated until all panelists had some measure of confidence for that parameter. The trainer repeated the training using the same pile technique for the remaining textural traits.

As part of the research for this study, Addie Waxman was recertified by Simplot to be a taste panelist for McDonald's French fries in 2012 and 2013 and maintains her certification with continued periodic training at the J. R. Simplot Technical Center in Caldwell, Idaho.

At monthly sampling intervals, potatoes were processed into French fries using a small scale method. Ten potatoes from each sample were washed and cut into 9.5mm French fry strips and divided into two piles. One pile was prepared for assessment of fry color, mottling, and sugar ends and used the center two strips of the potato. The other pile was prepared simultaneously for texture analysis by taking 4 strips from near the center of the potato. Both piles were blanched in their own pots at 80^{o}C for 6 minutes. The two piles were then hand dried separately on the counter top with paper towels, set onto individual metal baking racks, and dried in a Precision Drying Oven (Jouan, Inc., Winchester, VA) for 3 minutes at 50^{o}C. The two piles were fried in their own baskets in an F-49 Fryer (Wells Commercial Foodservice Equipment, St. Louis, MO) using canola oil at 190^{o}C for 4 minutes. After frying, the strips were removed from the fryer and dumped into separate piles onto a counter covered with paper towels. The strips were allowed to set for 1 minute at room temperature and then were fried in separate baskets a second time at 190^{o}C for 1 minute and 45 seconds. The strips from both baskets were dumped back onto the paper towel-covered countertop, still in their separate piles. The 20 strips for the fry color determinations were then lined up on a labeled paper towel with the stem end down for color analysis, then photographed. The USDA French Fry Color Chart (USDA, Washington, DC) was used to evaluate fry color, mottling, and sugar ends using a scale of 0 to 4 (Appendix 4). The 40 strips for textural analysis were allowed to cool for 1 minute before the taste panel began using a textural chart and visual appearance chart for the analysis (Figure 16).

At the end of the 1 minute cooling period, the 40 strips were placed before the panelists in a single pile. One panelist randomly selected 4 strips from the pile of 40 strips, broke the four strips in half, and all the panelists evaluated them for a cooked appearance and hollowness using the visual appearance chart. To receive a score of a 5, the interior had to possess a fluffy cooked appearance. A less than fluffy appearance was scored a 4. A partially cooked appearance was scored a 3 and a raw appearance was scored a 2 or 1, depending upon severity. A slight pulling away from the edges of the exterior shell was scored a 6. Additional hollowing was scored a 7 with severe hollowing scoring an 8 or 9 (Appendix 7).

Crispness was evaluated by having each panelist select two strips randomly from the pile, lining the strips side by side, and lightly biting the two strips with one's front teeth. To earn a score of a 5, the bite was to have a light, but notable and pleasing crispness. Less crispness earned a score of a 4. Lacking crispness was a 3. Scores of a 2 or 1 indicated that the fry had no crispness whatsoever and was basically lacking in exterior texture. A score of a 6 indicated that the crispness was still acceptable, but had a light crunch. A score of a 7 or higher indicated that the fry had a distinctive and undesirable crunch to the bite.

To evaluate exterior shell, each panelist randomly selected two strips from the pile and lined the strips up side by side. The procedure then was to use the front teeth to lightly bite partially through the two strips and then pull gently forward. A score of a five was earned when there was a slight tugging action required to pull the strips free from the closed teeth. If the tugging was perceived as slightly more exertion, then it was scored as a 6. Samples with more exertion earned higher scores from 7 to 10, indicating that the exterior shell was too tough. If the exertion was slightly less than desired to tear the strips, then sample earned an acceptable score of 4. If the sample easily tore, then the sample earned scored of 3 to 1, indicating that the exterior shell was unacceptably weak.

To evaluate mealiness, each panelist randomly selected two strips from the pile and lined up the strips side by side. The front teeth were used to bite through the sample and the tongue was used to separate the interior of the fry from the exterior shell using a rubbing action across the top of the mouth. A score of a five was earned when the interior of the fry had smaller, slightly firm granules. A score of a six had slightly larger, but acceptably sized, granules. A score of 7 or higher was earned when the granule sizes were unacceptably too large and coarse in size, indicative of undercooked potatoes. A score of a 4 was earned when the granules were smaller in size, but still acceptable. A score of a 3 and lower had very small granules or lacked granules at all, creating an unacceptable smooth texture.

Moistness was evaluated by each panelist randomly taking two strips from the pile and setting them on top of each other. The two strips were lined up over the molars on the bottom teeth and the molars of the top teeth bit down. A score of a 5 was earned when the strips were slightly dry, but with a hint of moisture to the pallet. Fries that were slightly moister than desired but still acceptable earned a score of a 6. Additional moisture at an unacceptable level earned scores of 7 and higher. A score of a 4 was earned when the sample was slightly drier than desired. An overly dry sample earned scores of 3 and lower.

If a panelist needed more samples to make the evaluation for any of the previous textural parameters, two fries were again selected and the process for that parameter was repeated.

Textural variation was based on a visual assessment of the sample. The taste panelists looked across the sample to check for uniformity of the sample. A score of five meant that the sample was uniform across the pile in terms of a pleasing fry color and acceptable length. A score of a six was earned when the sample contained some darkened fry color and shorter sized pieces. An unacceptable score of a 7 and higher indicated that the sample had a mixture of acceptable and unacceptable fry color with an increasing number of shorter pieces.

Textural defects were assessed for specific and highly unacceptable defects within the strip samples, such as excessive oiliness, greasy mouthfeel, and hard crunch. As the strips samples were being evaluated by the taste panelists for crispness, exterior shell, mealiness, and moistness, any texture defects were noted and recorded.

At monthly sampling intervals, five tubers per replication were evaluated for sucrose and glucose content (Appendix 5) and 10 tubers per sample were evaluated for sprout index (Appendix 6).

Analyzing Spider Plots in Textural Scores

When scoring for texture, a score of five indicates that the sample was perfect for that textural attribute. To illustrate textural differences to a greater degree, the perfect score is illustrated by a dotted line at the grid for a score of 5, creating a heptagonal shape. The most important textural attribute is normally placed at the top of the spider plot, which for this study is crispness. Lines pulling away from the dotted line diverge into non-heptagonal shapes indicating a less than perfect score (Gareau *et al.,* 2010)

Statistical Analysis

The data collected for texture, sprout index, fry color, mottling, sucrose and glucose was statistically analyzed using a Split Plot ANOVA with data collected from the following sampling times, at harvest, five months after harvest, and nine months after harvest for early, normal, and late harvest timings and the three varieties.

RESULTS

This study was originally designed to average the data for 2014 and 2015. However, the growing conditions between the two years had differences in regards to early season temperature extremes and the data was analyzed separately (Table 3 and Figure 3). Growing season weather for 2014 had temperatures closer to the ten year average for the area. However, 2015 had high temperatures during the early tuber bulking phase that were not present in 2014, possibly resulting in physiologically stressed potatoes.

Overall texture quality

At harvest in 2014, all three varieties were within grade, regardless of harvest timing (Figure 17). Early harvest and normal harvest had slightly lower internal appearance scores, indicating that the product has a marginally raw appearance. Late harvest produced scores close to a perfect score of a five, indicating that product from late harvest had the highest quality. Among the varieties, Russet Burbank had noticeably reduced internal appearance and crispness scores with early and normal harvest. Alpine Russet and Clearwater Russet had highly acceptable scores for all seven parameters and align with the dotted line for a perfect score to a greater degree than Russet Burbank.

Russet Burbank began the 2015 storage season with out of grade products from early harvest for crispness. Internal appearance scores were also out of grade for the early and late harvest, indicating that the product looked raw and undercooked. Alpine Russet had low crispness scores with early harvest and extremely low scores for internal appearance with late harvest. Clearwater Russet had highly acceptable scores for all harvest timings and all seven attributes (Figure 17).

At five months after harvest in 2014, the textural quality of Russet Burbank deteriorated severely as indicated by the loss of a heptagonal shape in the spider plot (Figure 18). Crispness scores were lowered for all three harvest timings, but had out of grade scores for early harvest, indicating that the texture was limp and lacked crispness. Alpine Russet also declined in crispness quality with early harvest resulting from out of grade, limp product. Clearwater Russet maintained highly acceptable scores for all three harvest timings and for all seven textural traits as indicated by the near perfect heptagonal shape of the spider plot.

At five months after harvest in 2015, Russet Burbank had deteriorated in crispness and internal appearance. Scores for the other five traits were declining as well, resulting in an amorphous shape within the spider plot and an overall out of grade product. Alpine Russet also diminished in textural quality with unacceptably low crispness and internal appearance scores as shown within the spider plot as flattened heptagons. Clearwater Russet textural scores remained highly acceptable in all seven categories with a nearly perfect heptagon shape on the spider plot (Figure 18).

At nine months after harvest in 2014, Russet Burbank declined severely in textural quality as shown by misshapen lines on the spider plot (Figure 19). Crispness scores with all three harvest timings were low and out of grade, indicative of unacceptably limp fries. Early harvest internal appearance scores were extremely low, resulting from product that looked raw and undercooked. Textural defect scores were very high for early and late harvests, indicating that fries possessed wholly undesirable traits for retail sale. Alpine Russet also declined in textural quality as indicated by a more trapezoidal shape on the spider plot. There was a severe decline in crispness scores, indicating that the French fries were limp and lacking crispness. Mealiness and exterior shell scores were low for Alpine Russet, indicating that the fries were overly smooth with weak shells. Clearwater Russet maintained optimal textural quality for six out of seven attributes, as shown with a congruent shape of the desired heptagon within spider plot. Only internal appearance was slightly out of grade. Crispness, the most important textural attribute, was maintained throughout the entire storage season with Clearwater Russet.

At nine months after harvest in 2015, the textural quality of Russet Burbank had severely deteriorated as shown by the completely amorphous shape on the spider plot. All seven textural attributes were out of grade indicating that the French fries were limp with weak shells, smooth in mealiness, raw in appearance and containing numerous visual defects. Alpine Russet scores were also very low with early harvest, being out of grade for crispness and mealiness. Late harvest scores were also low, but within grade, in numerous categories. However the cumulative effect was that fries made with Alpine Russet at nine months after harvest were out of grade. Clearwater Russet maintained highly acceptable texture scores in all seven categories at nine months after harvest. Exterior shell scores were high, indicating a tougher exterior shell, but remained within grade (Figure 19).

When the spider plots are defined by variety as opposed to harvest timing, the significant varietal differences are more evident. In 2014, Russet Burbank and Alpine Russet exhibited a gradual decline of textural quality over the nine month storage season, (Figures 20 and 22) whereas the Clearwater Russet maintained textural quality for the full storage season with minimal decline (Figure 21). In 2015, Russet Burbank and Alpine Russet textural quality worsened over the storage season, ending with out of grade scores

(Figures 20 and 22). However, Clearwater Russet began the storage season with highly acceptable textural scores and maintains in-grade product for the full nine month storage season (Figure 21).

Individual textural attributes

Crispness

In 2014, only variety had a significant influence on crispness (Table 10). However, in 2015, both harvest timing and variety had a significant effect on crispness at harvest, at five months after harvest, and at nine months after harvest. A significant variety by timing interaction was noted at harvest and at nine months after harvest.

External Shell

Harvest timing had no impact on external shell textural ratings on any sample date in 2014 or 2015 (Table 10). In contrast, variety significantly impacted external shell ratings on all sample dates in 2015, and at 9 months after harvest in 2014. In 2014 at nine months after harvest, a variety by timing interaction was noted.

Mealiness

Harvest timing had no significant effect on mealiness scores on any sampling date in 2014 or 2015 (Table 10). Variety significantly impacted mealiness scores at five months after harvest in 2014 and 2015 and at nine month after harvest in 2015.

Moistness

Harvest timing had no significant effect on moistness in 2014 (Table 10). Significant varietal differences were noted in 2014 at harvest and at nine months after harvest. In 2014 at nine months after harvest, a significant variety by timing difference was noted. In 2015, harvest timing and variety were significant at five months after harvest and at nine months after harvest.

Texture Variation

Harvest timing had no significant effect on texture variation in 2014 or 2015 (Table 10). Significant differences due to variety were observed at five months after harvest and nine months after harvest in 2014 and with all three sampling periods in 2015. In 2014, significant variety by timing interactions at five months and nine months after harvest were noted.

Texture Defects

In 2014, harvest timing and variety were significant only at nine months after harvest (Table 10). In 2015, harvest timing was not significant at any of the sampling periods, whereas variety had significant effect at harvest, five months after harvest, and at nine months after harvest. In 2014 at nine months after harvest, a significant variety by timing interaction was observed.

Internal Appearance

In 2014, significant differences were noted with timing at harvest, with variety at all three sampling periods, and with a variety by timing interaction at all three sampling periods (Table 10). In 2015, timing was significant only at harvest. Variety had significant differences at all three sampling periods.

General Observations made during French fry processing

Clearwater Russet was consistently dryer following the drying step than either Russet Burbank or Alpine Russet. Tackiness was minimal and there was less free moisture on the surface of the potato strips.

There was minimal oil sputtering when Clearwater Russet entered the fryer. In addition, the oil temperature didn’t decline as drastically as with Russet Burbank or Alpine Russet.

Fry Quality

Fry Color

In 2014, harvest timing had a significant influence on fry color at harvest and at five months after harvest with normal harvest having significantly darker color at harvest and late harvest having significantly lighter color at five months after harvest. In 2015, harvest timing had a significant influence on fry color at five and nine months after harvest. Late harvest had significantly darker fry color at five months after harvest and normal harvest having significantly darker fry color at nine months after harvest.

Although significant differences were noted among harvest timings in both 2014 and 2015, fry color remained acceptable for the full storage season (Figure 30). However, there were significant differences in fry color among varieties. Russet Burbank had consistently darker fry color than Alpine Russet or Clearwater Russet in both study years and throughout the storage season. Russet Burbank fries continued to darken over the nine month storage period. Alpine Russet had highly acceptable fry color in 2014 but in 2015, Alpine Russet darkened over the storage season. Clearwater Russet had highly acceptable fry color throughout the full nine month storage season in both years of the study. . A significant variety by timing interaction was observed at five and nine months after harvest in 2015 showing Russet Burbank increasing in fry color over the storage season.

Glucose

Glucose levels overall were not affected by harvest timing in 2014 or 2015, but did vary by variety. (Figures 28 and 29). In both 2014 and 2015, Russet Burbank had higher glucose levels than Alpine Russet or Clearwater Russet during the entire storage season.

Sucrose

Sucrose levels were not affected by harvest timing in 2014 or 2015, but did vary by variety and year (Figures 30 and 31). Alpine Russet had higher sucrose levels that Russet

Burbank or Clearwater Russet during the entire storage season. Sucrose levels for all three varieties were elevated in 2015 compared to 2014.

Mottling

No significant incidence of mottling was noted for either study year (data not shown).

Sprout Index

Sprout index levels were not affected by harvest timing in 2014, but were affected by variety. Russet Burbank had higher sprout index levels, but maintained acceptable sprouting levels for the full storage season. In 2015, sprout index was affected by harvest timing. Late harvest experienced earlier sprouting and to a greater degree than early or normal harvest.

DISCUSSION

The key objective of this study was to determine if harvest timing had a negative effect on end product textural quality of French fries of three processing varieties. The results of this study indicate harvest timing does impact texture. However, harvest timing did not affect the seven parameters of texture equally. It was observed that the textural parameters of crispness was more affected by harvest timing than exterior shell, mealiness, moistness, texture variation, texture defects or internal appearance. Whereas it is true that all of the studied textural traits contribute to the overall texture, crispness is the first impression of quality that a consumer will make when tasting a French fry (Miranda & Aguilera, 2006). French fries lacking that initial light crispy crunch are normally regarded as low quality product by the consumer (Lisinska & Golubowska, 2005). Therefore, while it is important to know the impact of harvest timing upon all seven textural traits, it is especially important to know the effect of harvest timing on crispness.

Under normal growing conditions, an early harvest was shown to negatively impact crispness scores mid-way through a nine month storage season with unacceptable scores earned at five months then nine months after harvest. When the study was conducted under conditions of high temperatures during early bulking during 2015, the impact of early harvest was decidedly greater. Potatoes at early harvest had unacceptable crispness scores on the day of harvest, at five months after harvest and at nine months after harvest.

Harvest timing did not significantly impact the textural traits of external shell, mealiness, moistness, texture variation, texture defects, or internal appearance. However, it should be noted that early harvest tended to have scores that were within grade, but slightly more skewed towards out of grade product. The cumulative effect of this response can be perceived as poor quality by the consumer.

The negative effect of early harvest on French fry textural quality can be traced back to issue of physiological maturity. Driskill *et al.,* (2007) found that harvesting at physiological maturity will produce higher quality processing potatoes, which will in turn produce higher quality French fries. This is most likely due to the physiochemical properties of mature potatoes that allow them to endure the rigors of French fry processing (Fennema, 1996; Liu *et al., 2003)*.

Potatoes harvested at physiological maturity tend to have more dry matter, higher specific gravities, a higher number and larger starch molecules, and less free moisture. These traits tend to increase the likelihood of producing higher quality French fries (Driskoll *et al.,* 2007). In addition, mature potatoes tend to have cell walls and middle lamellas that are structurally sound and able to withstand the harsh conditions of French fry processing while experiencing less decline over time in storage.

In contrast, potatoes harvested prior to physiological maturity often have less dry matter, lower specific gravities with more free water and smaller starch molecules, which can adversely affect crispness (Jaswal, 1969). In essence, potatoes harvested prior to physiological maturity have additional free water with smaller and fewer starch cells that are unable to absorb the extra moisture during the frying process (Singh & Kaur, 2009). The heat of frying removes a significant portion of the free water from the potato strips (Miranda & Aguilera, 2006). However, if a potato has more free water when processed, that extra moisture within the potato strip may not be absorbed by the starch cells and can continue to diffuse to the newly made crust and make the end product limp and soggy (Singh & Kaur, 2009).

In this study, the crispness scores indicated that textural quality declined due to the fries having a weak and soggy texture, not due to excessively crunchy texture. Therefore, the concept of potatoes having lower specific gravities, weaker structural integrity, and additional water with smaller starch molecules associated with an early harvest is the most likely explanation for the deterioration of crispness texture.

Harvest timing did play a role in regards to texture, but significant differences in textural quality were observed among varieties as well. In fact, the main effects of variety were more consistently significant than the effects of harvest timing. Overall, Russet Burbank and Alpine Russet both had out of grade textural scores in storage, however, Russet Burbank had lower scores than Alpine Russet. Russet Burbank was out of grade for texture at five and nine months after harvest in 2014 and at harvest, five, and nine months after harvest in 2015. Alpine Russet was out of grade at five and nine months after harvest in both 2014 and 2015. Russet Burbank also deteriorated earlier in the storage season and to a greater degree than either Alpine Russet or Clearwater Russet during 2015.

In comparison, Clearwater Russet maintained excellent textural quality throughout the full nine month storage season in both study years. In 2014, the textural quality at nine months remained equal to the textural quality observed at harvest. Even when grown under conditions of high heat at early bulking stage in 2015, Clearwater Russet maintained high textural scores for nine full months of storage.

It was also noted that the effect of variety exhibited congruent results between crispness and internal appearance. Both texture characteristics indicated that Clearwater Russet maintained higher quality at harvest, at five months and nine months after harvest in both study years. Additional study is needed to confirm the relationship between crispness and internal appearance. However, due to the similarities between the two parameters, it may be possible to determine end product quality by internal appearance alone if a full texture taste panel is unavailable.

The large differences in textural scores between the varieties can be attributed in part to the different specific gravity levels of each variety. Russet Burbank had low specific gravities in 2014 and even lower specific gravities in 2015. The storage season began with lower quality potatoes and declined over time in storage, especially in 2015. Clearwater Russet, however, had significantly higher specific gravities than Russet Burbank or Alpine Russet in 2014. In 2015, the Clearwater Russet exhibited good heat tolerance in the field and produced potatoes with even higher specific gravities than found in 2014. The higher specific gravities contributed greatly to providing better quality French fries that maintained high textural scores throughout the storage season.

When integrating the disciplines of plant science and food science of potatoes and French fries to the results of this study, it becomes apparent why Clearwater Russet maintained high quality textural scores in both 2014 and 2015 storage seasons when compared to Russet Burbank and Alpine Russet. Clearwater Russet had significantly higher specific gravities than either of the other varieties, increasing over time with each harvest. However, it was during French fry processing in the laboratory that the benefit of having higher specific gravity became evident.

At the crucial steps of drying, and frying, Clearwater Russet exhibited subjective traits of dryer potato strips and later a higher quality French fry. At the end of the drying step, Clearwater Russet appeared to consistently dry to a greater degree with less tackiness and free moisture than either the Russet Burbank or the Alpine Russet. With a dryer exterior of the strip, the Clearwater Russet strips may have had the foundation for creating the exterior crust which in turn would create the desirable crispy texture and exterior shell of a French fry.

Not only were the strips were subjectively dryer to the touch, but upon entering the fryer, the Clearwater Russet strips had less oil sputtering due to the presence of free water. It was also noted that the temperature of the frying oil did not drop as drastically as with the other two varieties. This further implies that the strips were fried at a more constant temperature for a longer period of time than Russet Burbank or Alpine Russet. The potential maintenance of the frying temperature for a longer portion of the timed fry would increase the evaporation of free water from the interior of the fry and increase the crispiness of the exterior of the French fry. These unexpected findings were observed outside of the parameters of the original study, however, further research is warranted to examine the different reactions at each step of processing for the varieties.

It was also noted by the taste panelists that the Clearwater Russet exhibited a longer post-frying holding time, maintaining its desirable texture for longer after frying than the Russet Burbank or the Alpine Russet. This is most likely due to the properly cooked interior of the French fry as well as the well-formed structure of the crust. Although this wasn't an intended aspect of this study, the consistent reports by the taste panelists are intriguing and deserve additional research.

Harvest timing had minimal effects on fry color, glucose, sugar ends, and mottling. In contrast, Russet Burbank had significantly darker fry color, higher glucose levels, and a much higher incidence of sugar ends than Alpine Russet or Clearwater Russet.

CONCLUSIONS

Early harvest has a negative effect on French fry texture, particularly the textural attribute of crispness. French fries produced from early harvested potatoes declined in quality to a greater degree over the nine month storage season than French fries produced from normal or late harvests. Product from early harvest was out of grade at five months after harvest in 2014 and out of grade at harvest in 2015. French fries produced from tubers harvested at or near physiological maturity had the highest textural quality and maintained that quality longer in the nine month storage season.

The three processing varieties displayed significant differences with regard to textural quality. Russet Burbank deteriorated rapidly in textural quality over the nine month storage season with out of grade product as early as at harvest. Alpine Russet declined in textural quality at five months after harvest with continued deterioration through the nine month storage period. Clearwater Russet, however, produced high quality product throughout the nine month storage season with very acceptable textural quality scores.

Fry quality was within acceptable parameters for fry color, sugar ends, and mottling throughout the full nine month storage season for all harvest timing treatments and varieties. However, varietal differences were noted with regards to fry color. Even though the fry color was fully acceptable, Russet Burbank was significantly darker in color than either Clearwater Russet or Alpine Russet in both study years. In addition, in 2015, Russet Burbank had significantly more sugar ends than the two other varieties. No significant differences in mottling were observed for all harvest timing treatments and varieties.

Clearwater Russet appears to be a variety that performs well in the field under optimal and adverse growing conditions. This indicates that Clearwater Russet possesses certain stress tolerant traits and may require fewer fertility and water inputs during the growing season. These characteristics could prove valuable for growers and processors as they seek out varieties that are more efficient, heat and drought tolerant, and sustainable. In addition, Clearwater Russet produces high quality French fries that maintain high textural acceptability over the course of a full nine month storage season. The combination of these positive traits enabled Clearwater Russet to be chosen as the new “Mac-Fry” variety by McDonald’s in September, 2016.

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Table 10. F-values for the textural attributes of crispness, exterior shell, mealiness, moistness, texture variation, texture defects, and internal appearance at three different harvest timings; early, normal, and late of three processing varieties, Russet Burbank, Clearwater Russet, and Alpine Russet.

	F Value													
Effect	**Crispness**		**Exterior Shell**		**Mealiness**		**Moistness**		**Texture Variation**		**Texture Defects**		**Internal App**	
	2014	2015	2014	2015	2014	2015	2014	2015	2014	2015	2014	2015	2014	2015
At Harvest														
Timing	0.35^{ns}	6.99*	2.28^{ns}	1.22^{ns}	0.30^{ns}	0.06^{ns}	0.38^{ns}	1.56^{ns}	0.07^{ns}	0.56^{ns}	4.33^{ns}	2.22^{ns}	15.62*	9.72*
Variety	3.15*	11.42*	1.56^{ns}	8.52*	1.22^{ns}	0.40^{ns}	2.44*	1.86^{ns}	0.07^{ns}	5.52*	0.58^{ns}	4.61*	11.31*	12.14*
V x T	2.92^{ns}	3.40*	2.64^{ns}	1.65^{ns}	2.22^{ns}	2.46^{ns}	0.74^{ns}	0.69^{ns}	0.91^{ns}	2.35^{ns}	0.71^{ns}	1.62^{ns}	6.46*	2.34^{ns}
5 MAH														
Timing	2.18^{ns}	5.67*	7.94^{ns}	3.18^{ns}	0.23^{ns}	2.40^{ns}	0.67^{ns}	10.50*	2.64^{ns}	1.15^{ns}	0.50^{ns}	2.33^{ns}	1.12^{ns}	3.00^{ns}
Variety	58.23*	13.40*	0.00^{ns}	15.41*	7.15*	3.92*	1.31^{ns}	21.12*	13.79*	31.23*	2.00^{ns}	25.86*	8.50*	12.21*
V x T	1.77^{ns}	1.86^{ns}	0.74^{ns}	1.68^{ns}	1.27^{ns}	2.72^{ns}	1.58^{ns}	2.19^{ns}	10.67*	1.98^{ns}	0.50^{ns}	1.43^{ns}	3.22*	0.70^{ns}
9 MAH														
Timing	1.07^{ns}	3.00^{ns}	0.35^{ns}	3.21^{ns}	0.68^{ns}	4.33^{ns}	0.71^{ns}	7.99*	3.72^{ns}	0.85^{ns}	8.17*	0.78^{ns}	1.22^{ns}	4.10^{ns}
Variety	19.36*	32.13*	9.37*	13.35*	3.04^{ns}	7.36*	5.28*	3.64*	23.29*	25.25*	15.72*	34.11*	16.08*	14.49*
V x T	2.71^{ns}	3.98*	3.54*	0.89^{ns}	1.02^{ns}	0.47^{ns}	4.51*	1.01^{ns}	7.12*	0.27^{ns}	5.09*	1.49^{ns}	5.77*	1.18^{ns}

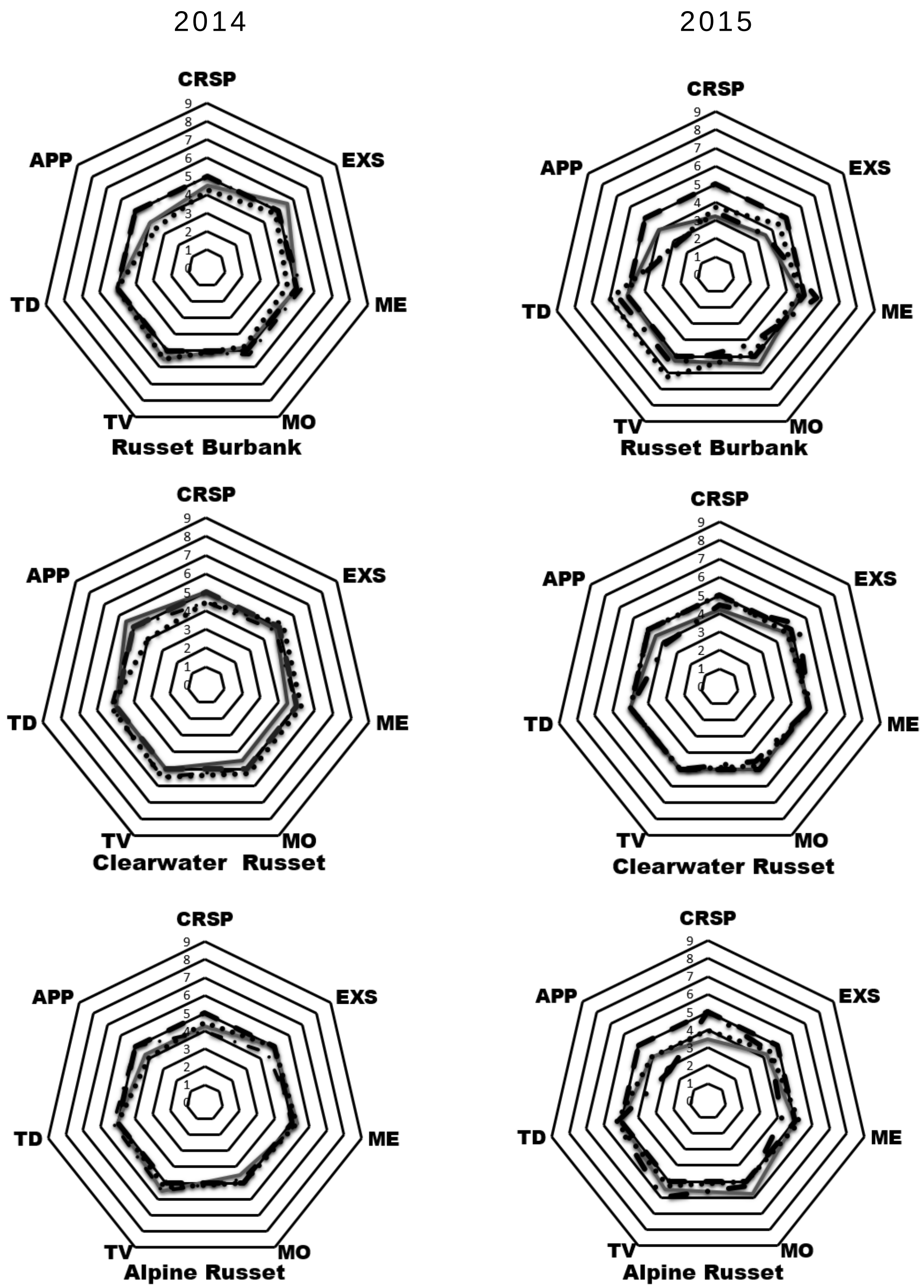
V=Variety, T=Timing, ns = not significant, * denotes significance

Figure 16. Textural analysis score card for evaluation of French fries.

Category	1	2	3	4	5	6	7	8	9
	Less Crisp							Crunchy	
Crispness									
	Weak							Tough	
Exterior Shell									
	Smooth							Coarse	
Mealiness									
	Dry							Wet	
Moistness									
					Norm			Excessive	
Texture Variation									
					None			Excessive	
Texture Defects									
	Raw Center							Hollow Center	
Internal Appearance									

J. R. Simplot, 2012

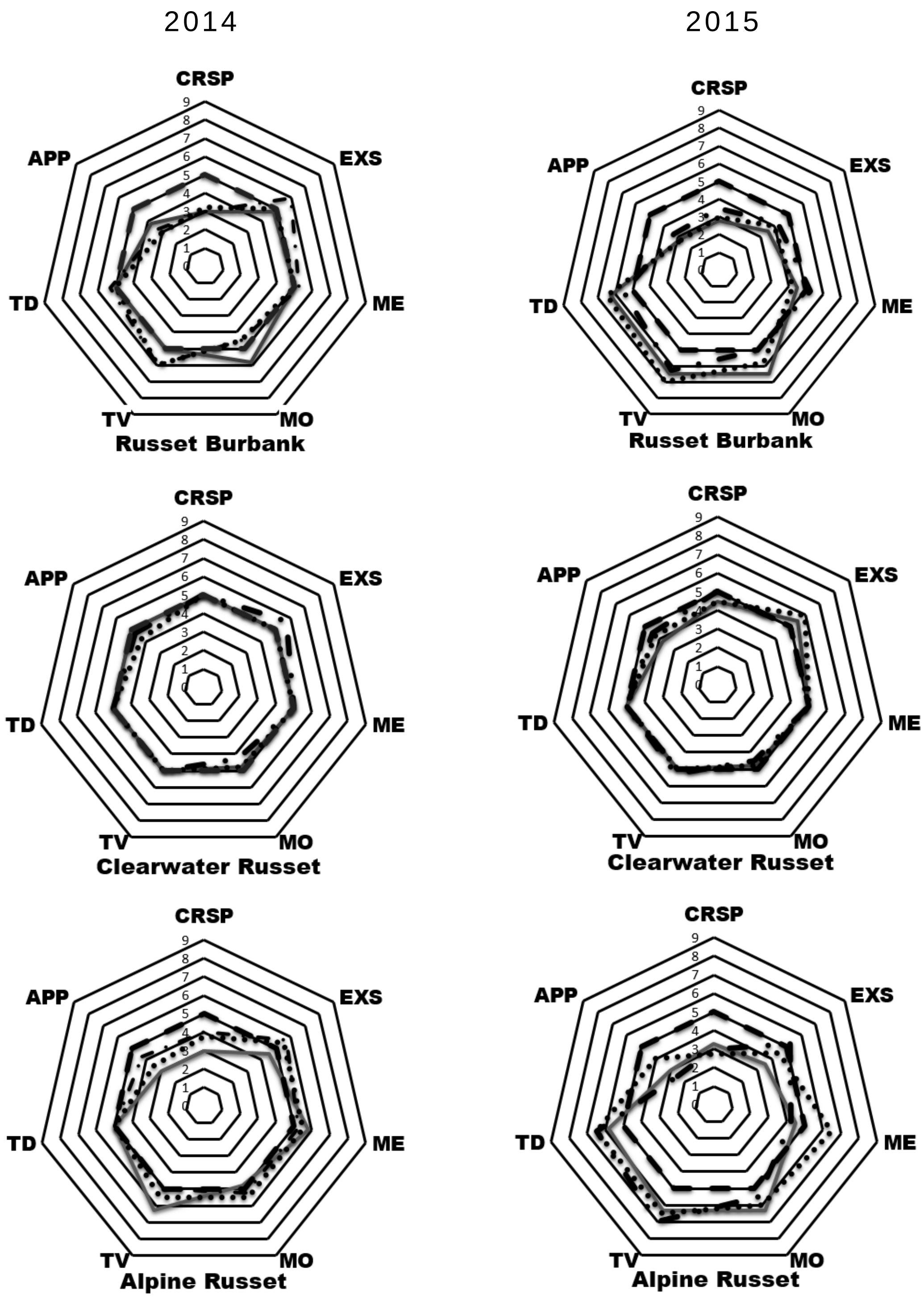
Figure 17. Texture evaluation of Russet Burbank, Clearwater Russet, and Alpine Russet at harvest in 2014 and 2015.



CRSP = Crispness, EXS = Exterior Shell, ME=Mealiness, MO=Moisture, TV=Texture Variation, TD=Texture Defects, APP=Appearance

Early Harvest ● ● ● Normal Harvest ▬ ● Late Harvest ▬ ▬ Perfect Score

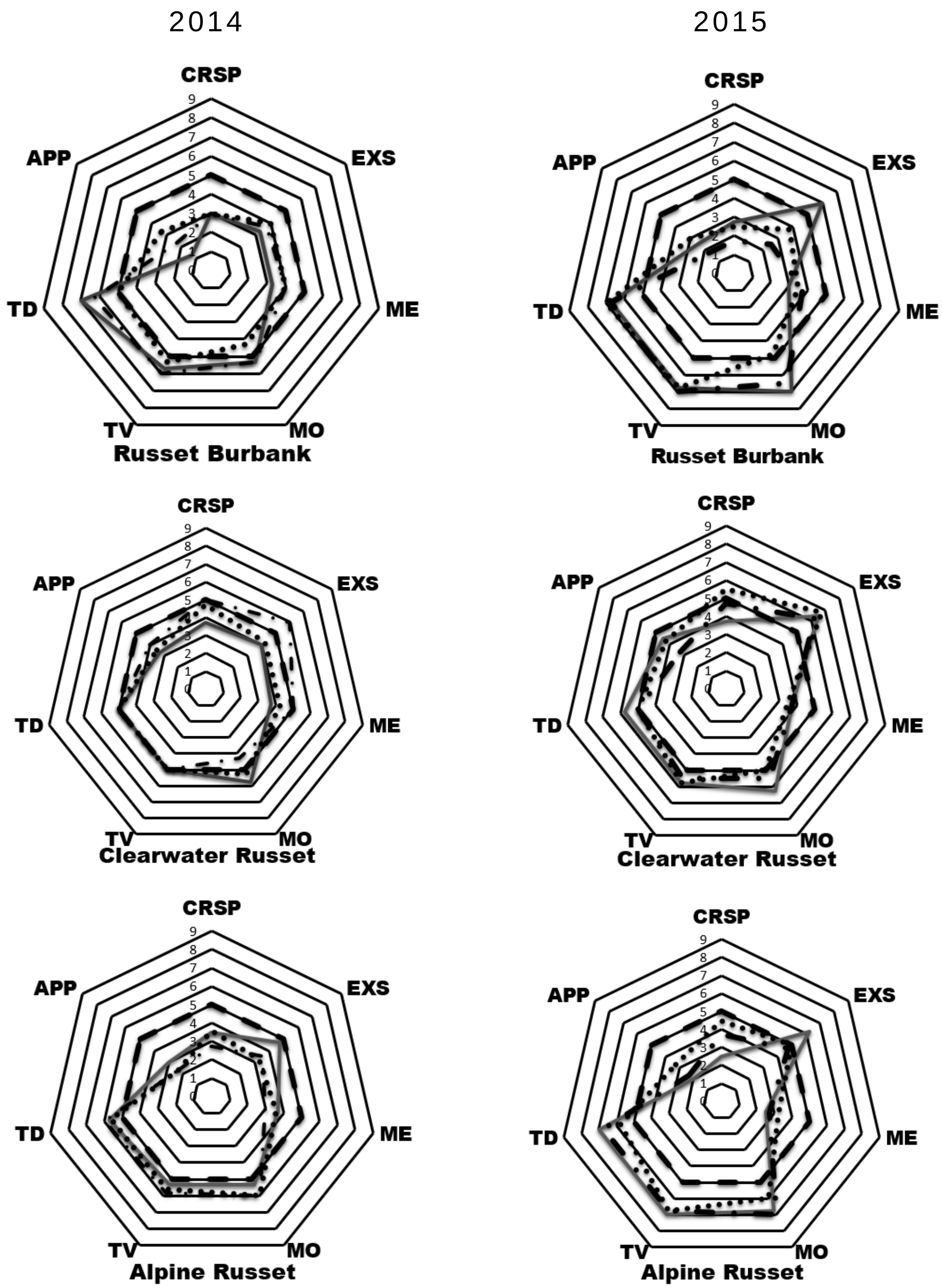
Figure 18. Texture evaluation of Russet Burbank, Clearwater Russet, and Alpine Russet at five months after harvest in 2014 and 2015.



CRSP = Crispness, EXS = Exterior Shell, ME=Mealiness, MO=Moisture, TV=Texture Variation, TD=Texture Defects, APP=Appearance

Early Harvest ● ● ● Normal Harvest ▬ ● Late Harvest ▬ ▬ Perfect Score

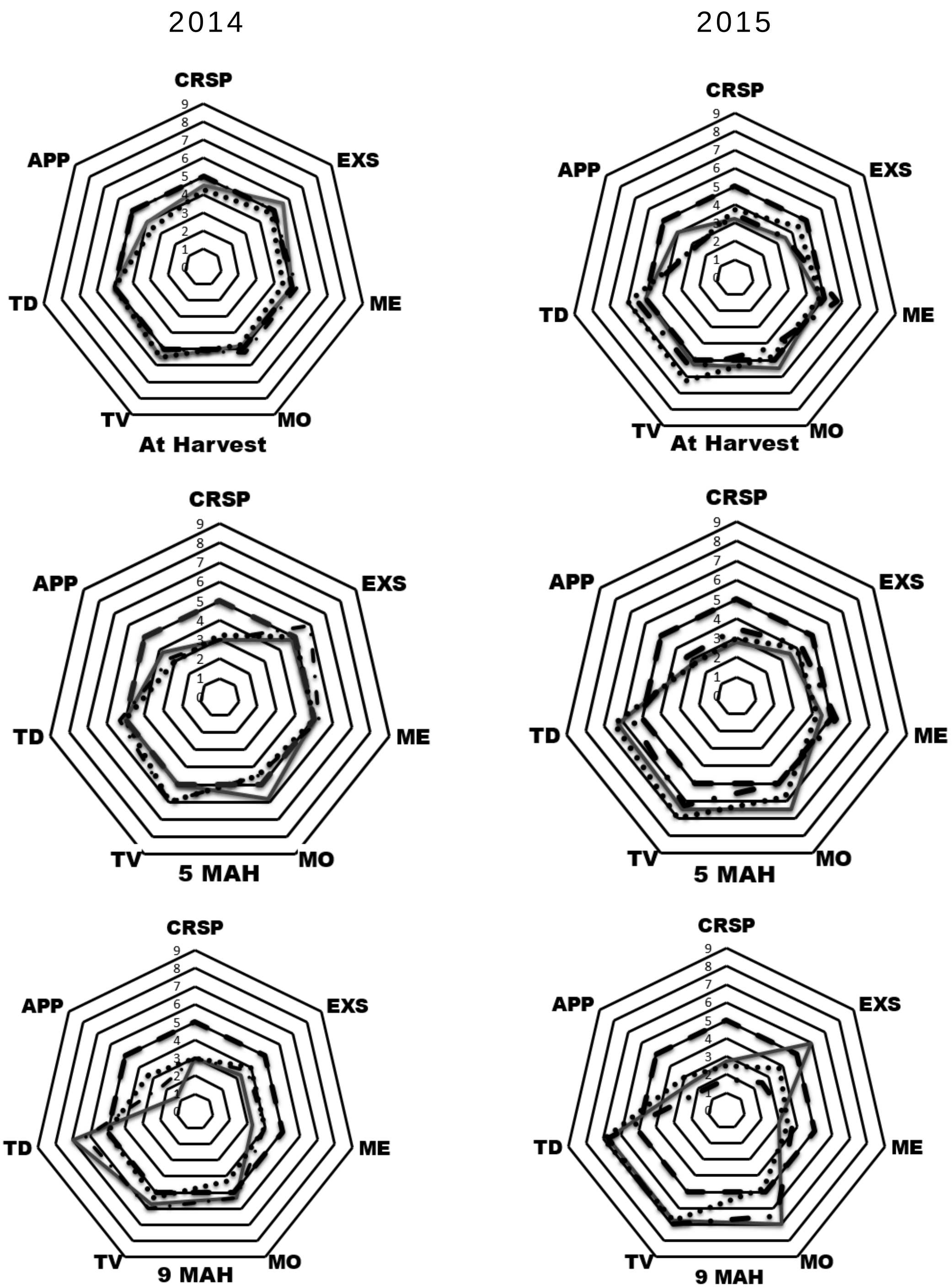
Figure 19. Texture evaluation of Russet Burbank, Clearwater Russet, and Alpine Russet at nine months after harvest in 2014 and 2015.



CRSP = Crispness, EXS = Exterior Shell, ME=Mealiness, MO=Moisture, TV=Texture Variation, TD=Texture Defects, APP=Appearance

Early Harvest ● ● ● Normal Harvest ▬ ● Late Harvest ▬ ▬ Perfect Score

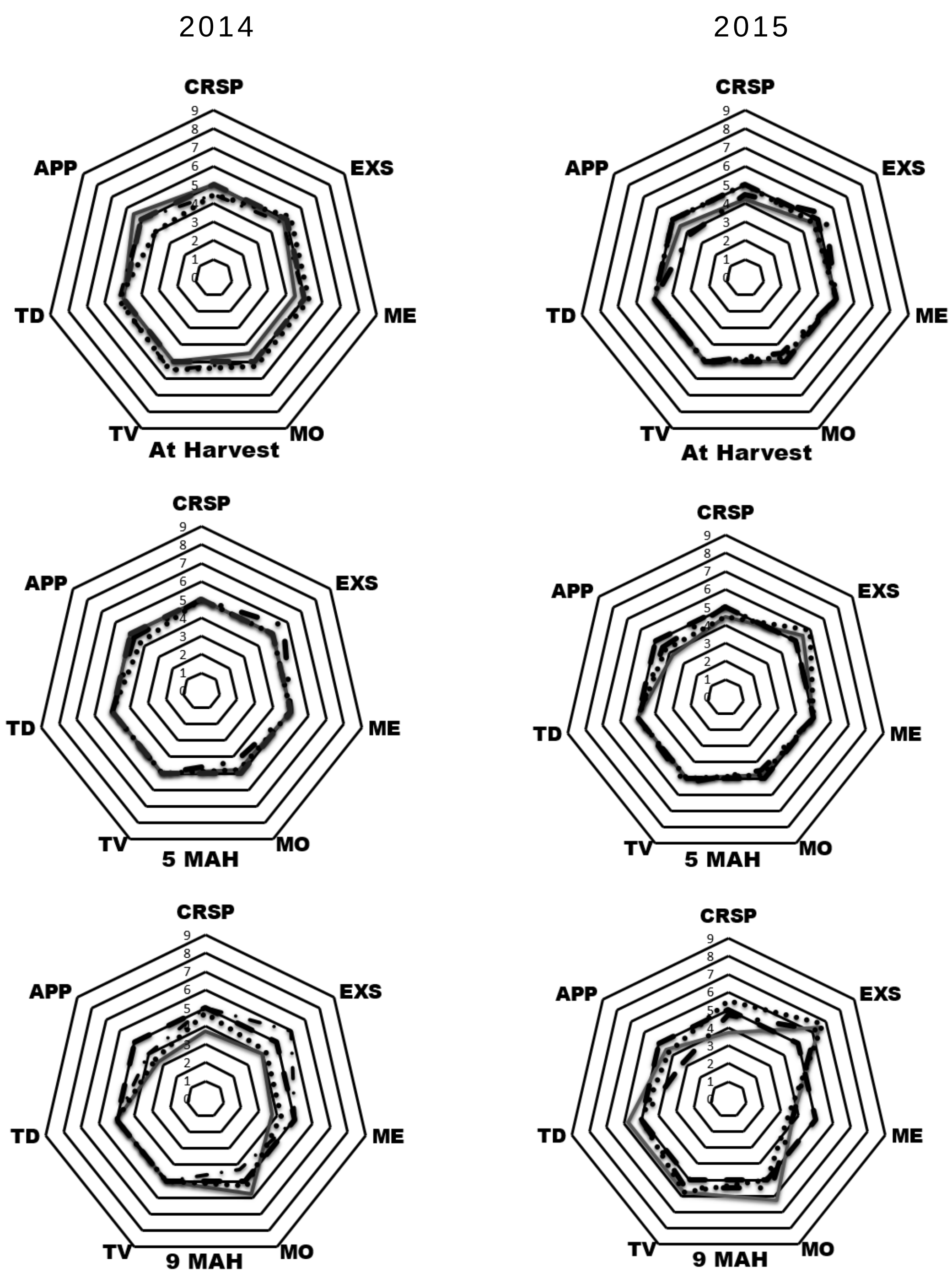
Figure 20. Texture evaluation of Russet Burbank at harvest, at five months after harvest, and at nine months after harvest in 2014 and 2015.



CRSP = Crispness, EXS = Exterior Shell, ME=Mealiness, MO=Moisture, TV=Texture Variation, TD=Texture Defects, APP=Appearance, 5 MAH=5 Months after Harvest, 9MAH=Nine Months after Harvest

Early Harvest · Normal Harvest · Late Harvest · Perfect Score

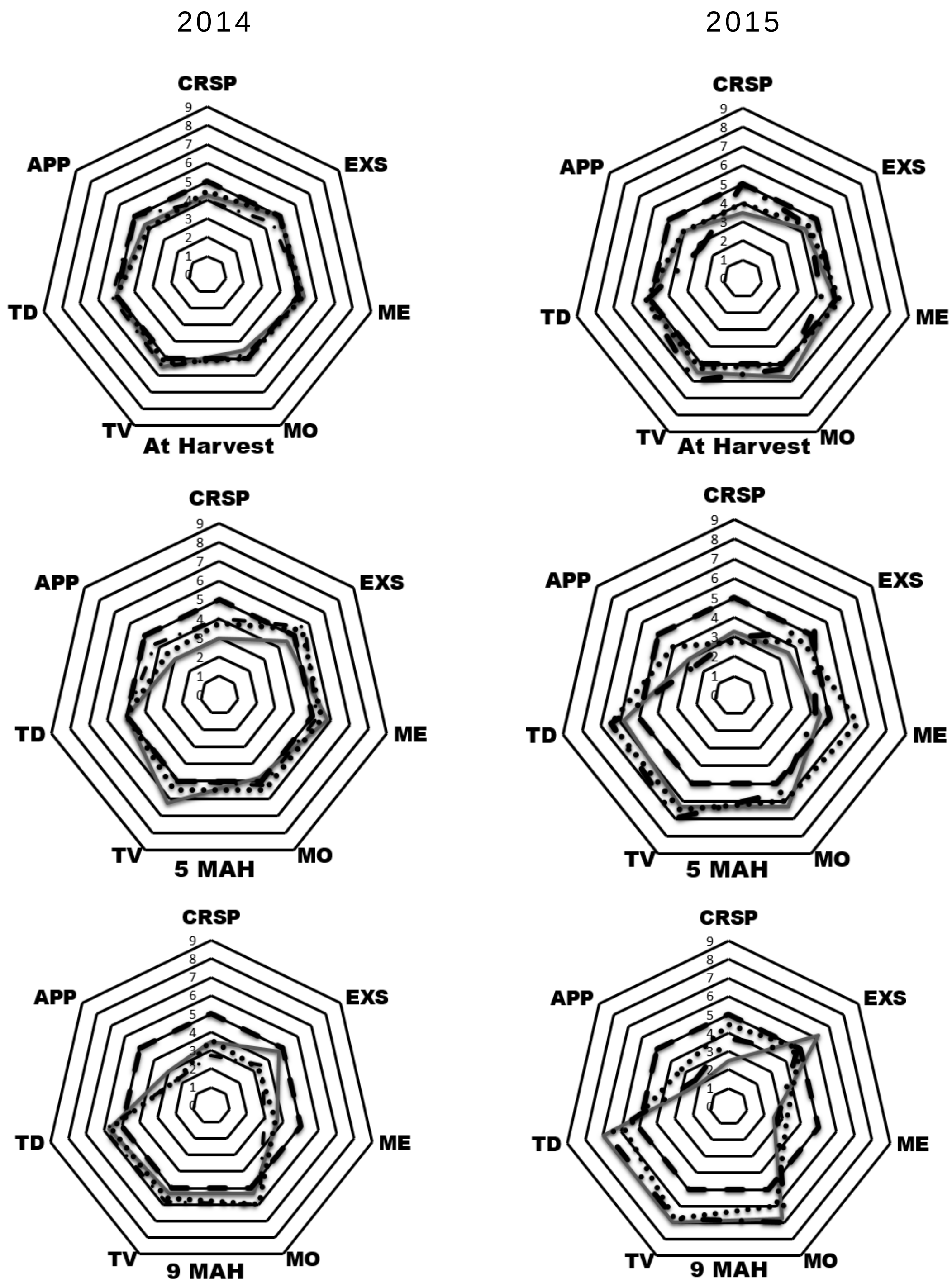
Figure 21. Texture evaluation of Clearwater Russet at harvest, at five months after harvest, and at nine months after harvest in 2014 and 2015.



CRSP = Crispness, EXS = Exterior Shell, ME=Mealiness, MO=Moisture, TV=Texture Variation, TD=Texture Defects, APP=Appearance, 5 MAH=5 Months after Harvest, 9MAH=Nine Months after Harvest

Early Harvest · Normal Harvest · Late Harvest · Perfect Score

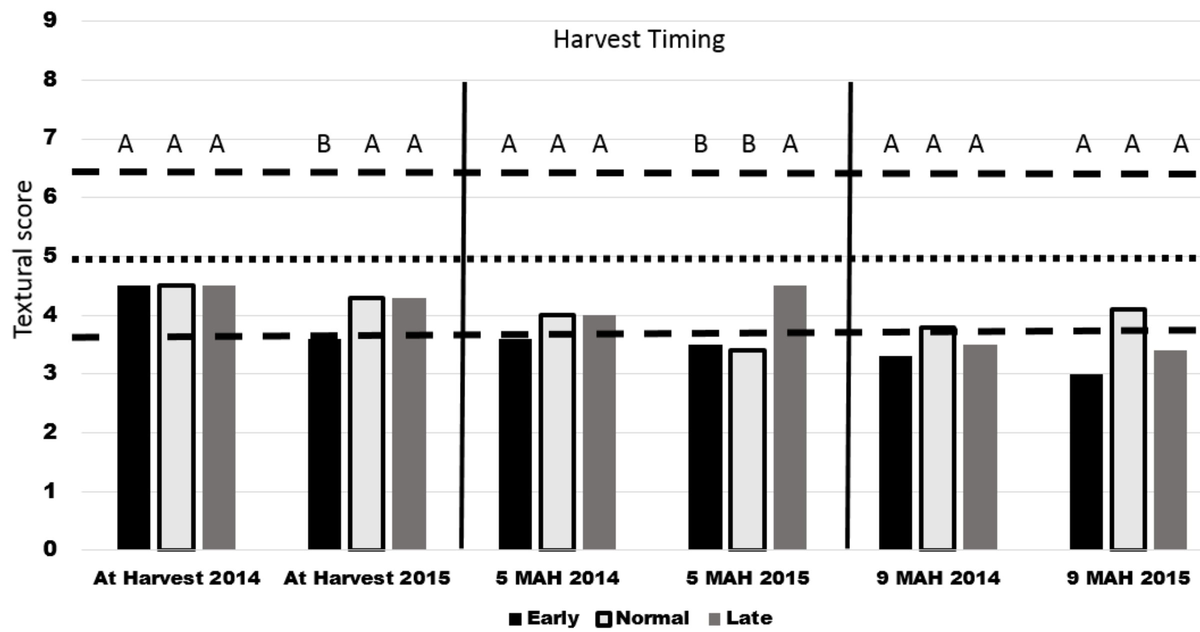
Figure 22. Texture evaluation of Alpine Russet at harvest, at five months after harvest, and at nine months after harvest in 2014 and 2015.

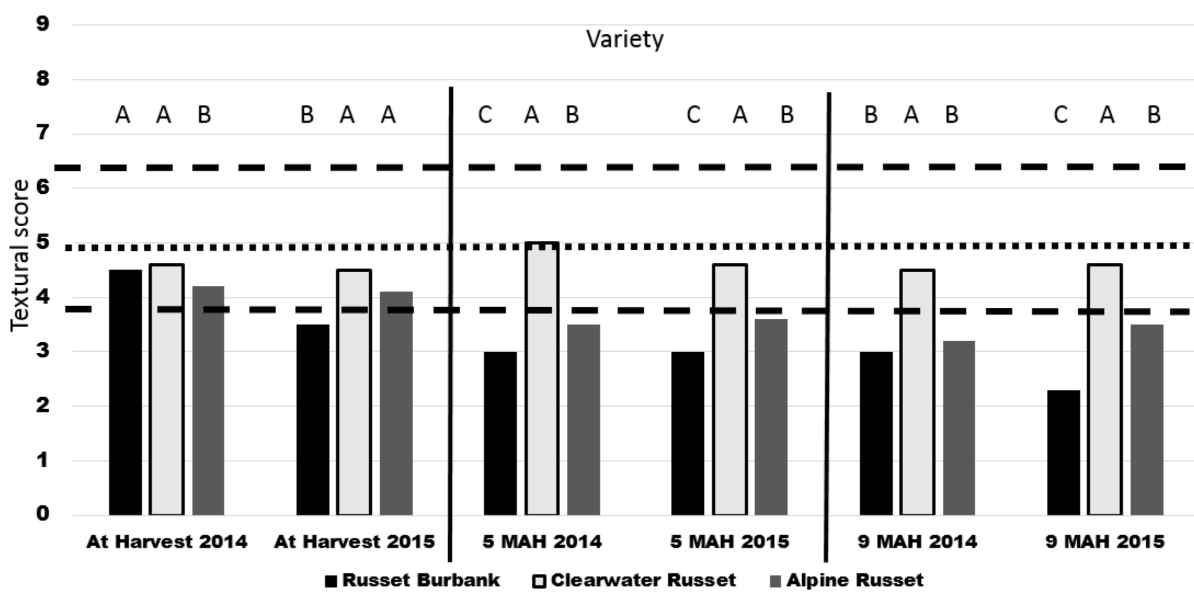


CRSP = Crispness, EXS = Exterior Shell, ME=Mealiness, MO=Moisture, TV=Texture Variation, TD=Texture Defects, APP=Appearance, 5 MAH=5 Months after Harvest, 9MAH=Nine Months after Harvest

Early Harvest ● ● ● Normal Harvest ▬ ● Late Harvest ▬ ▬ Perfect Score

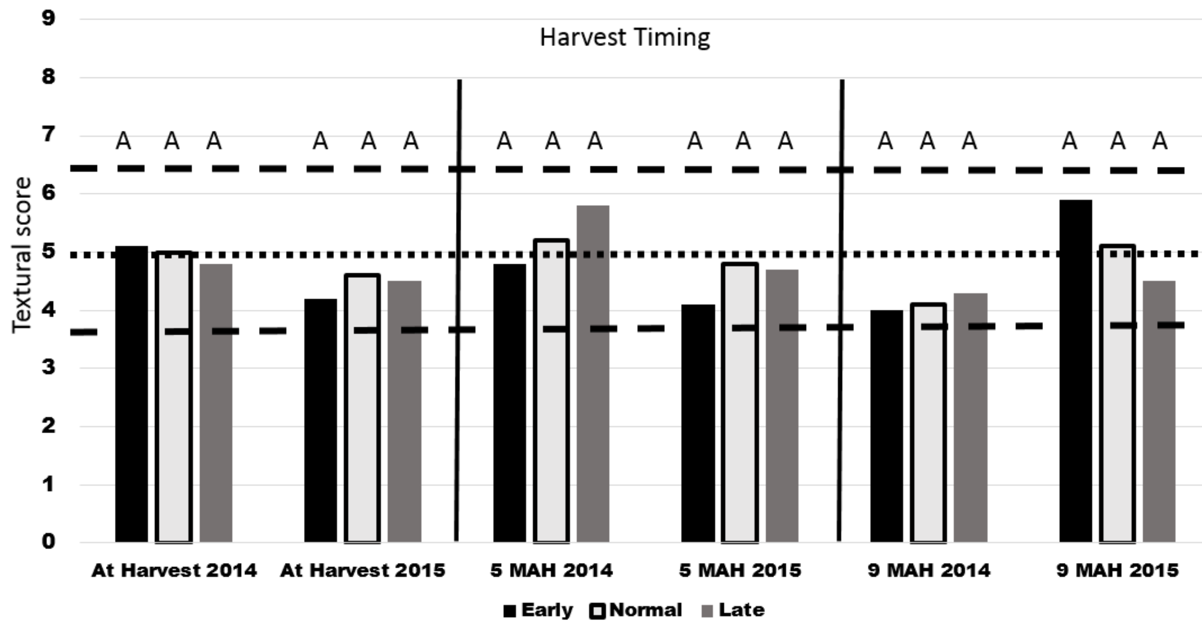
Figure 23. Summary of crispness scores in French Fries as effected by harvest timing and variety over nine months of storage for potatoes grown in Parma, ID during 2014 and 2015. Values are means of four replications.

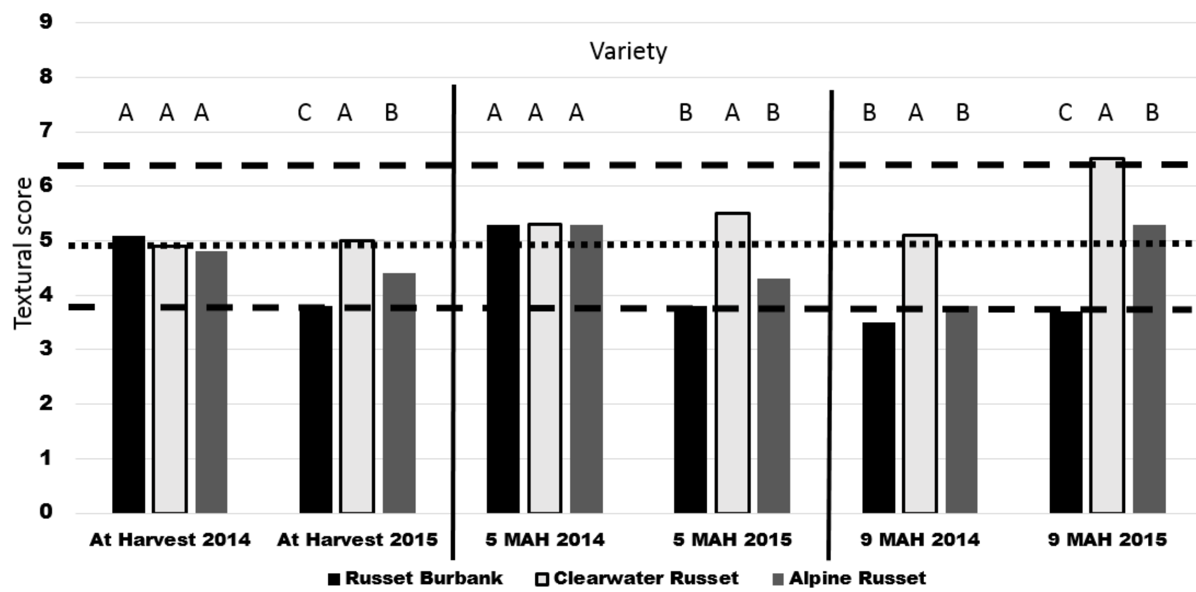




Means with same number are not significantly different at $p<0.05$.
5 MAH = Five Months after Harvest; 9 MAH = Nine Months after Harvest
Dotted line = perfect score of 5. Dashed line = acceptable range

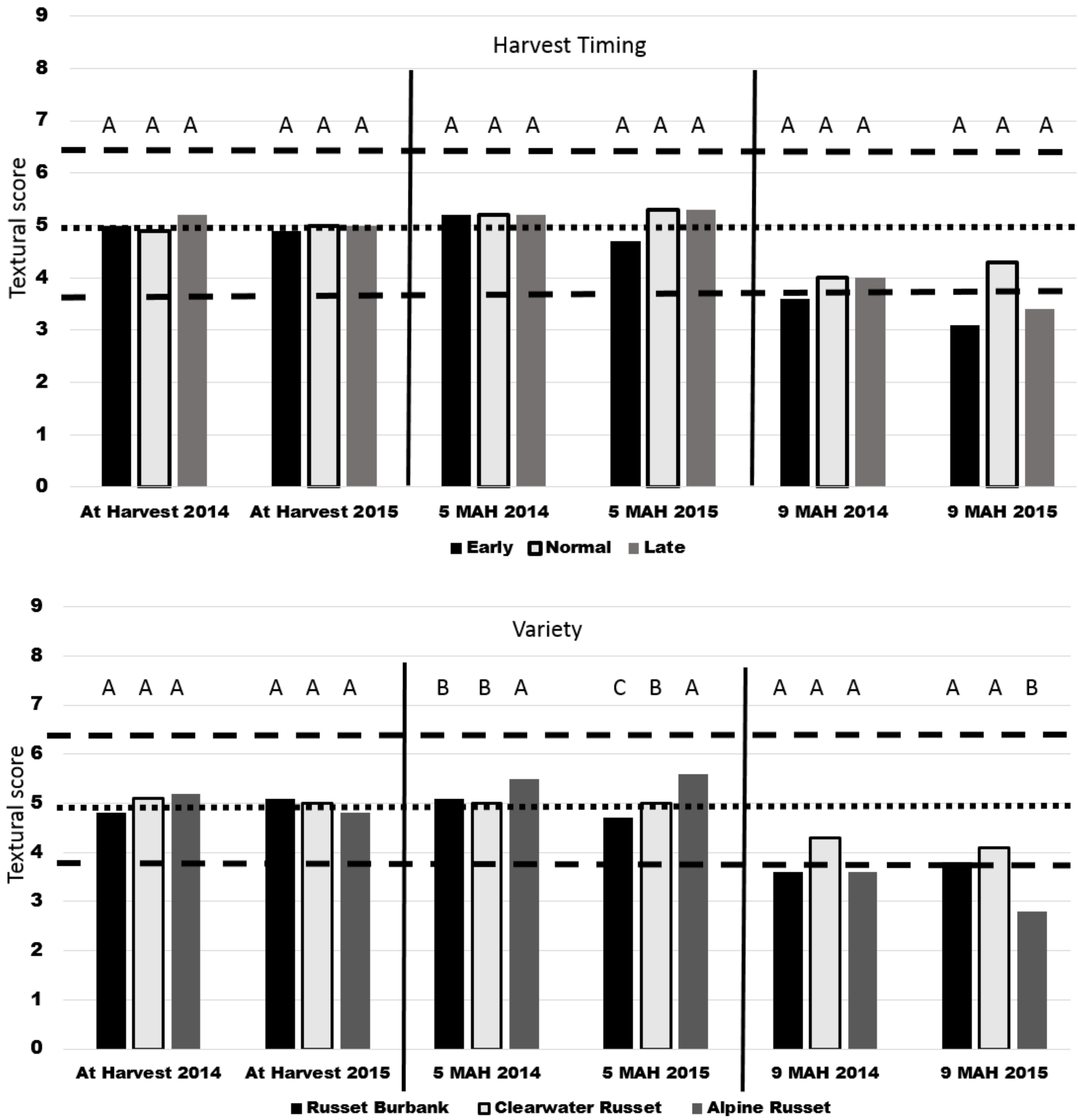
Figure 24. Summary of exterior shell scores in French Fries as effected by harvest timing and variety over nine months of storage for potatoes grown in Parma, ID during 2014 and 2015. Values are means of four replications.





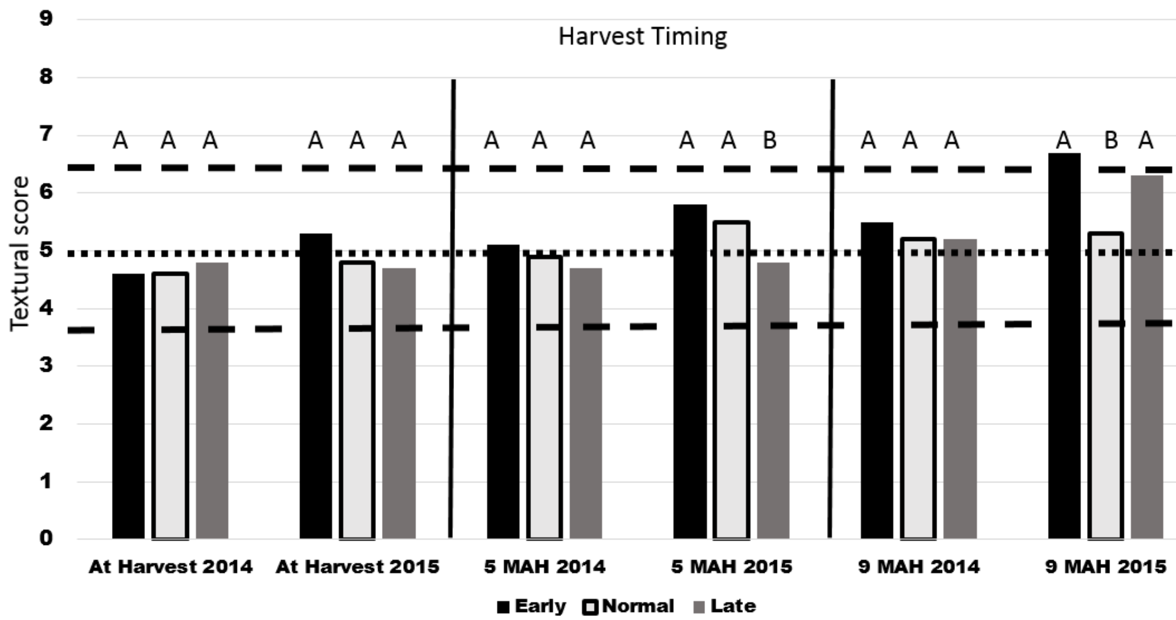
Means with same number are not significantly different at $p<0.05$.
5 MAH = Five Months after Harvest; 9 MAH = Nine Months after Harvest
Dotted line = perfect score of 5. Dashed line = acceptable range

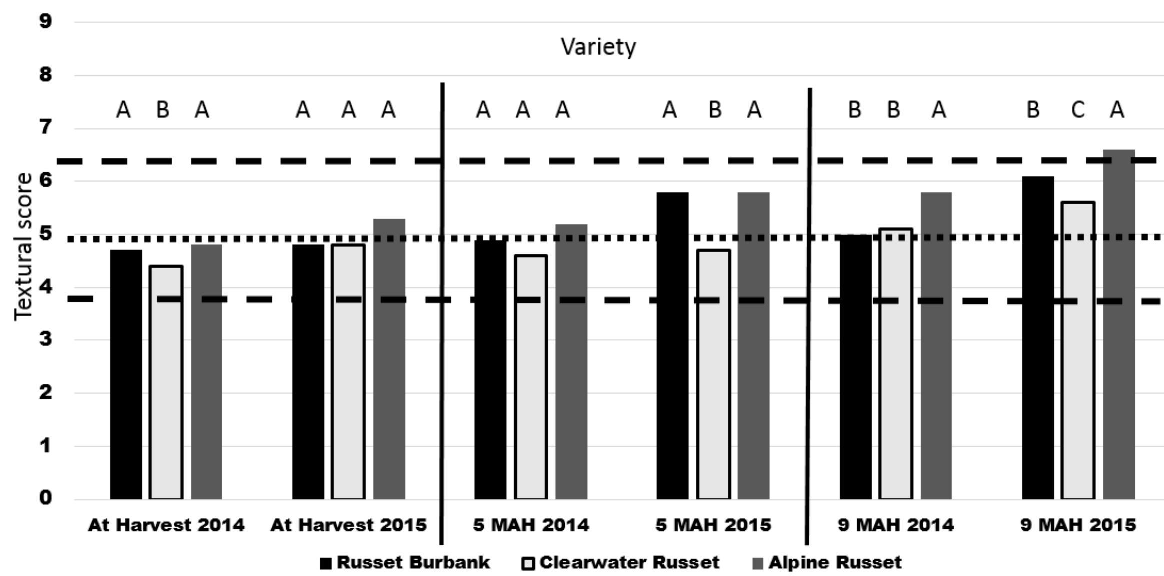
Figure 25. Summary of mealiness scores in French Fries as effected by harvest timing and variety over nine months of storage for potatoes grown in Parma, ID during 2014 and 2015. Values are means of four replications.



Means with same number are not significantly different at $p<0.05$.
5 MAH = Five Months after Harvest; 9 MAH = Nine Months after Harvest
Dotted line = perfect score of 5. Dashed line = acceptable range

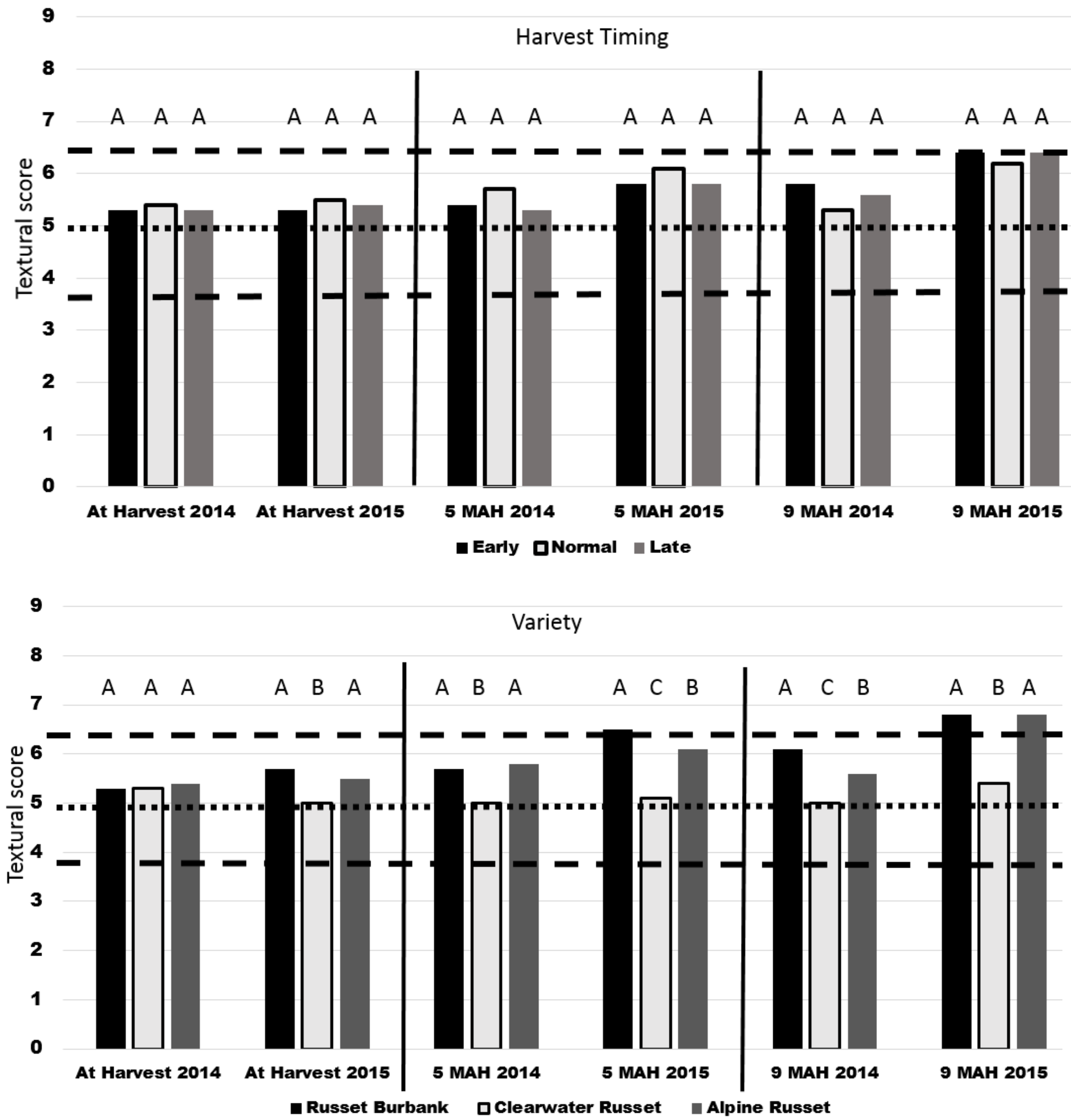
Figure 26. Summary of moistness scores in French Fries as effected by harvest timing and variety over nine months of storage for potatoes grown in Parma, ID during 2014 and 2015. Values are means of four replications.





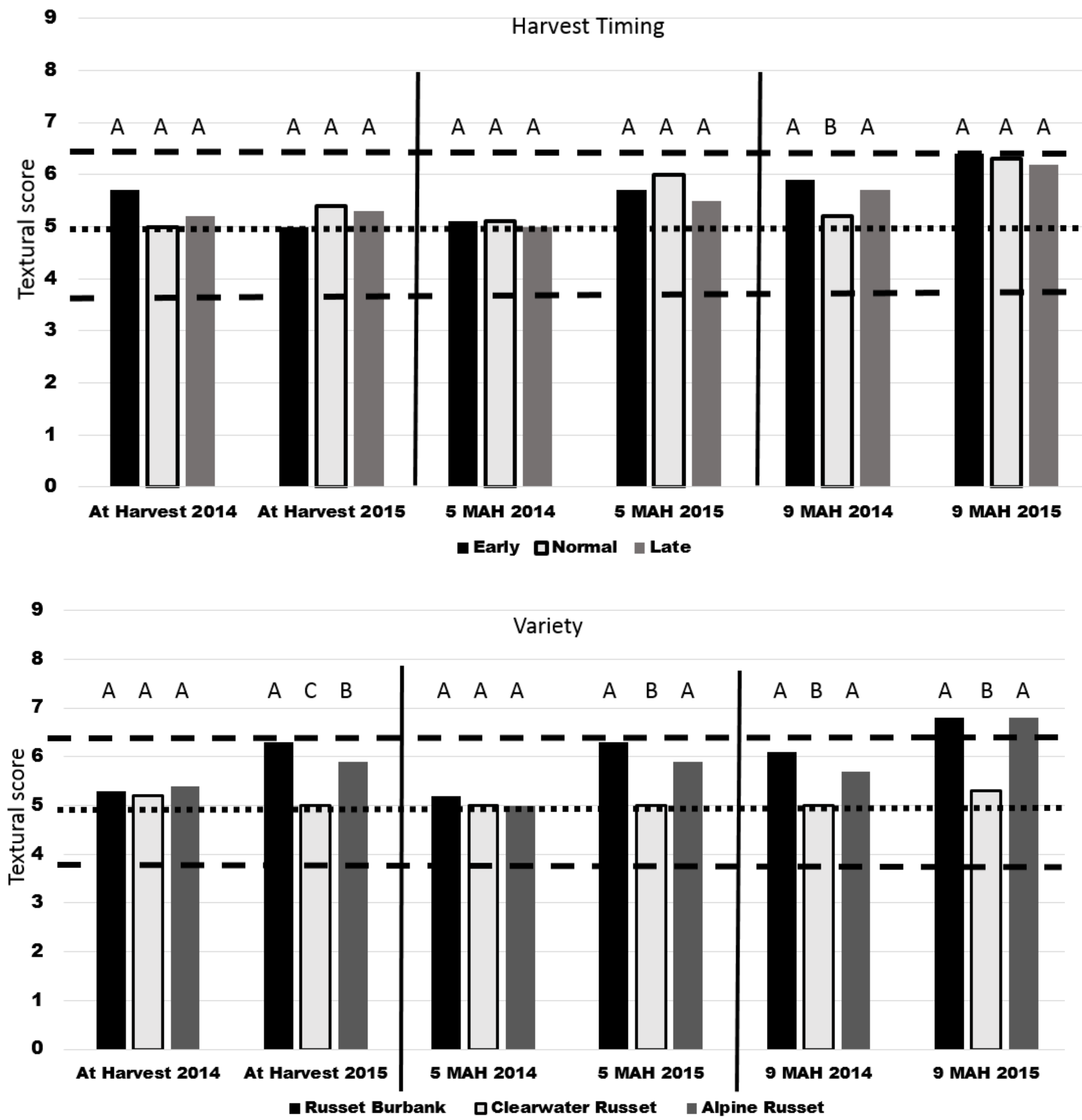
Means with same number are not significantly different at $p<0.05$.
5 MAH = Five Months after Harvest; 9 MAH = Nine Months after Harvest
Dotted line = perfect score of 5. Dashed line = acceptable range

Figure 27. Summary of texture variation scores in French Fries as effected by harvest timing and variety over nine months of storage for potatoes grown in Parma, ID during 2014 and 2015. Values are means of four replications.



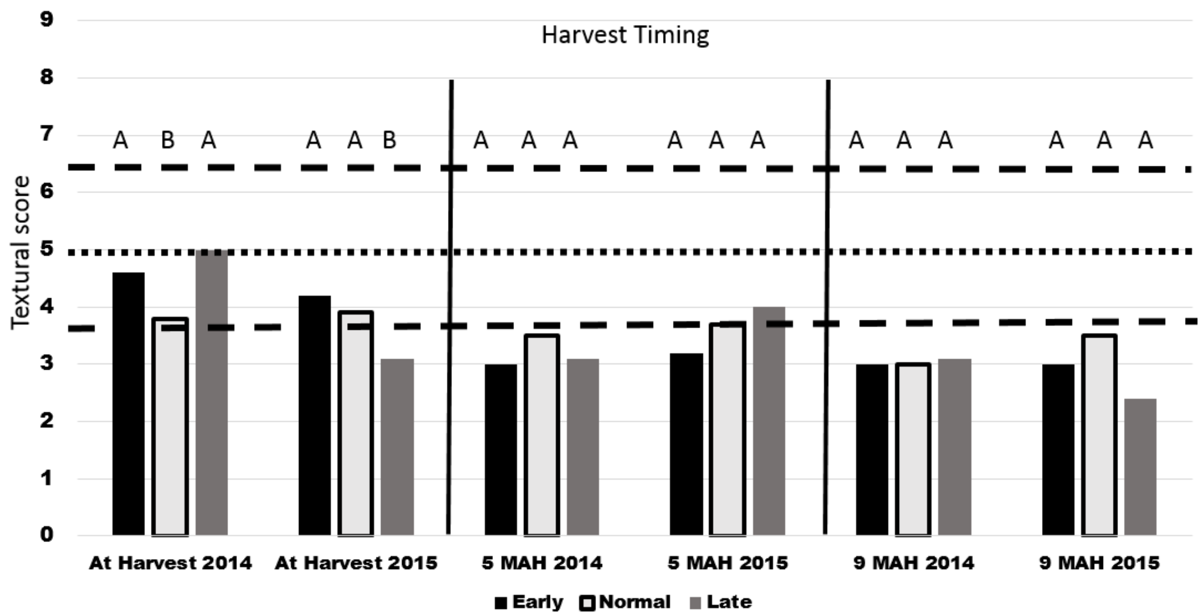
Means with same number are not significantly different at $p<0.05$.
5 MAH = Five Months after Harvest; 9 MAH = Nine Months after Harvest
Dotted line = perfect score of 5. Dashed line = acceptable range

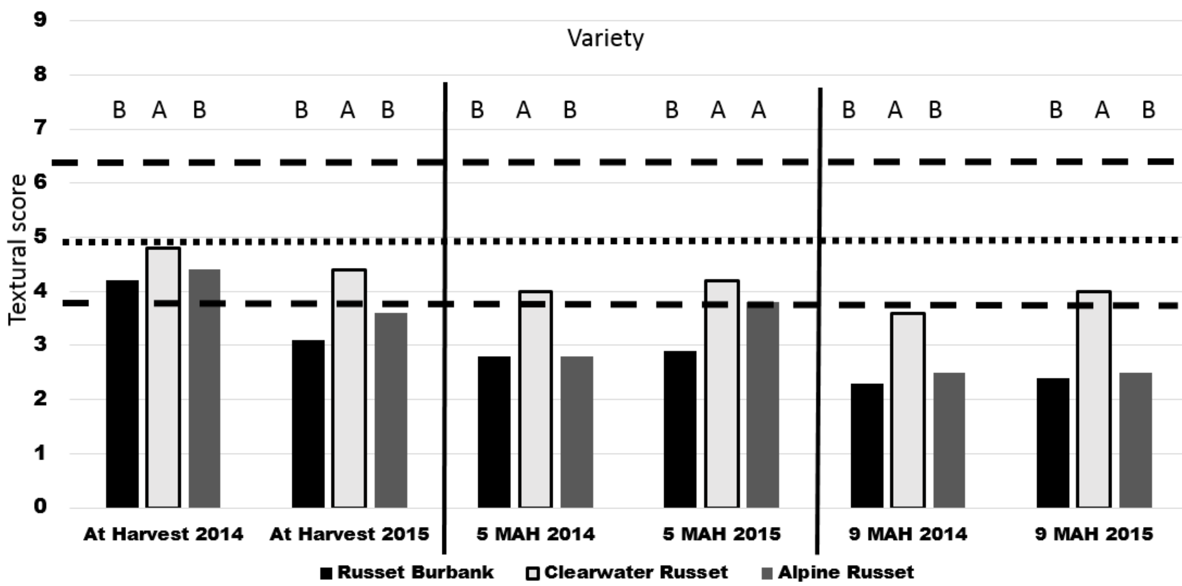
Figure 28. Summary of texture defects scores in French Fries as effected by harvest timing and variety over nine months of storage for potatoes grown in Parma, ID during 2014 and 2015. Values are means of four replications.



Means with same number are not significantly different at $p<0.05$.
5 MAH = Five Months after Harvest; 9 MAH = Nine Months after Harvest
Dotted line = perfect score of 5. Dashed line = acceptable range

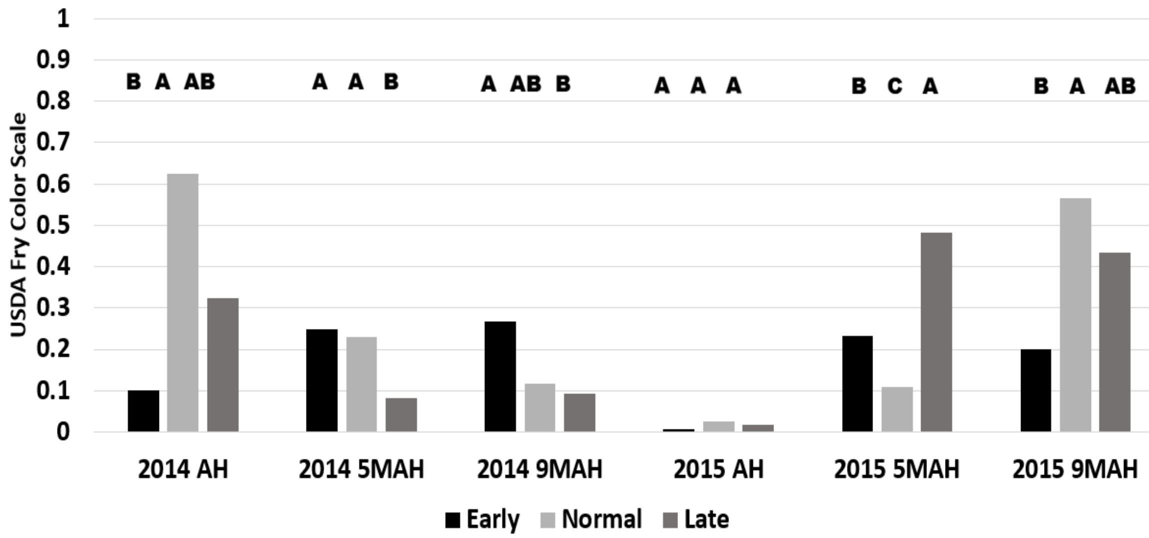
Figure 29. Summary of internal appearance scores in French Fries as effected by harvest timing and variety over nine months of storage for potatoes grown in Parma, ID during 2014 and 2015. Values are means of four replications.





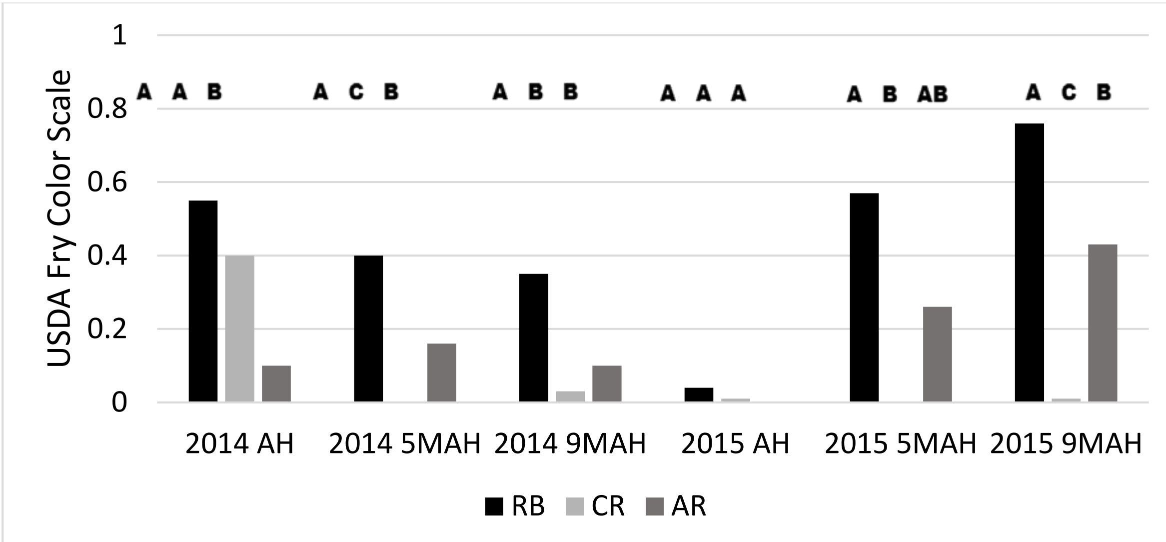
Means with same number are not significantly different at $p<0.05$.
5 MAH = Five Months after Harvest; 9 MAH = Nine Months after Harvest
Dotted line = perfect score of 5. Dashed line = acceptable range

Figure 30. Fry color of three harvest timings; early, normal, and late, of three processing varieties over nine months of storage at 8.3°C in 2014 and 2015.



AH = at harvest, 5 MAH = five months after harvest, 9 MAH = nine months after harvest
Early = early harvest; normal = normal harvest; late = late harvest
Means with same letter are not significantly different at $p<0.05$.
Fry color evaluated on the USDA fry color score of 0 to 4.
Axis was adjusted to 0 to 1 to show significant differences

Figure 31. Fry Color of three processing varieties over nine months of storage at 8.3°C; Russet Burbank, Clearwater Russet, and Alpine Russet, at three harvest timings; early, normal, and late in 2014 and 2015.



AH = at harvest, 5 MAH = five months after harvest, 9 MAH = nine months after harvest
RB= Russet Burbank, CR = Clearwater Russet, AR = Alpine Russet
Means with same letter are not significantly different at $p<0.05$.
Fry color evaluated on the USDA fry color score of 0 to 4. Axis was adjusted to 0 to 1 to show significant differences

Figure 32. Glucose levels (mg/g) of three processing varieties over 36 weeks of storage at 8.3ºC; Russet Burbank, Clearwater Russet, and Alpine Russet, at three harvest timings; early, normal, and late in 2014.

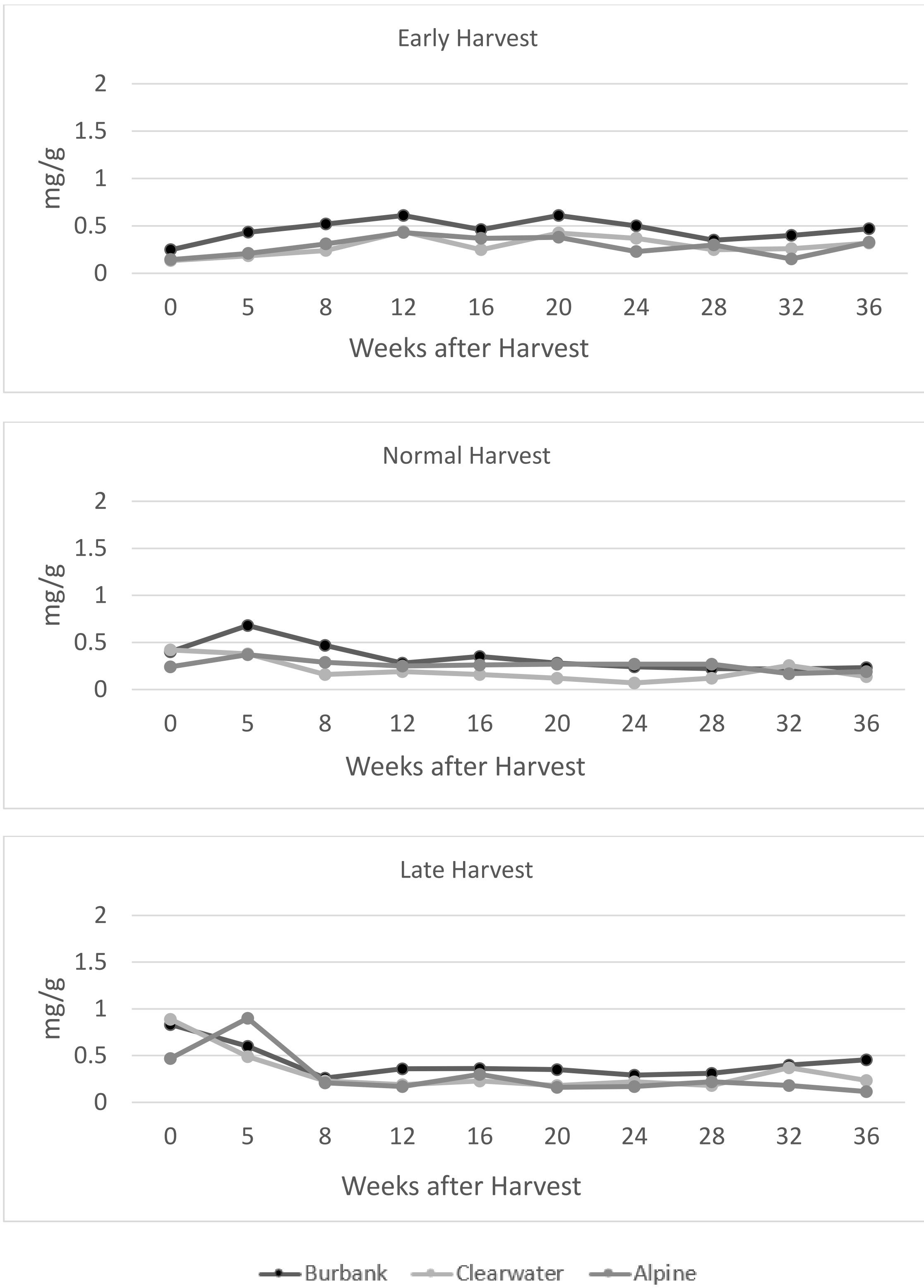


Figure 33. Glucose levels (mg/g) of three processing varieties over 36 weeks of storage at 8.3°C; Russet Burbank, Clearwater Russet, and Alpine Russet, at three harvest timings; early, normal, and late in 2015.

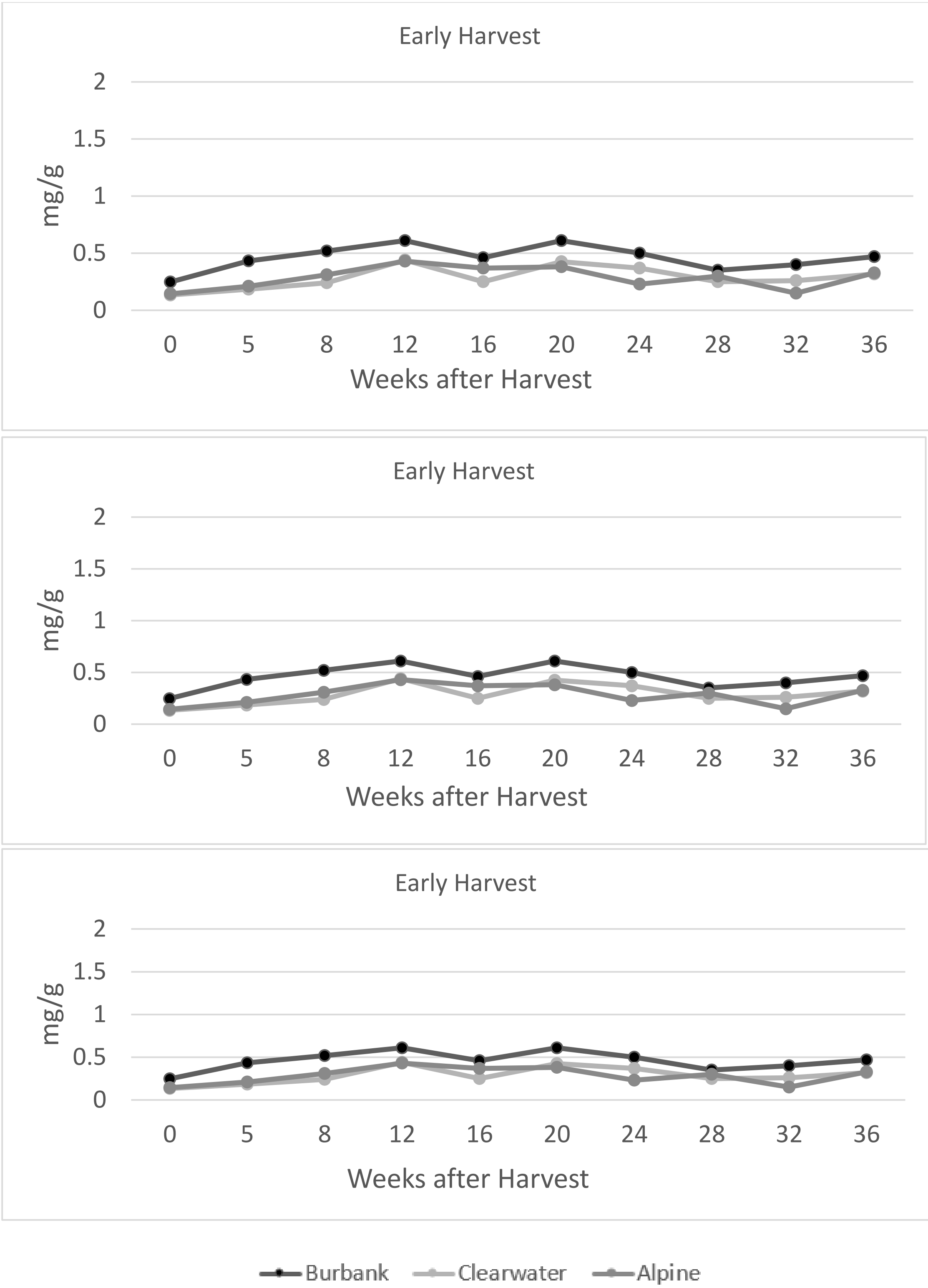


Figure 34. Sucrose levels (mg/g) of three processing varieties over 36 weeks of storage at 8.3°C; Russet Burbank, Clearwater Russet, and Alpine Russet, at three harvest timings; early, normal, and late in 2014

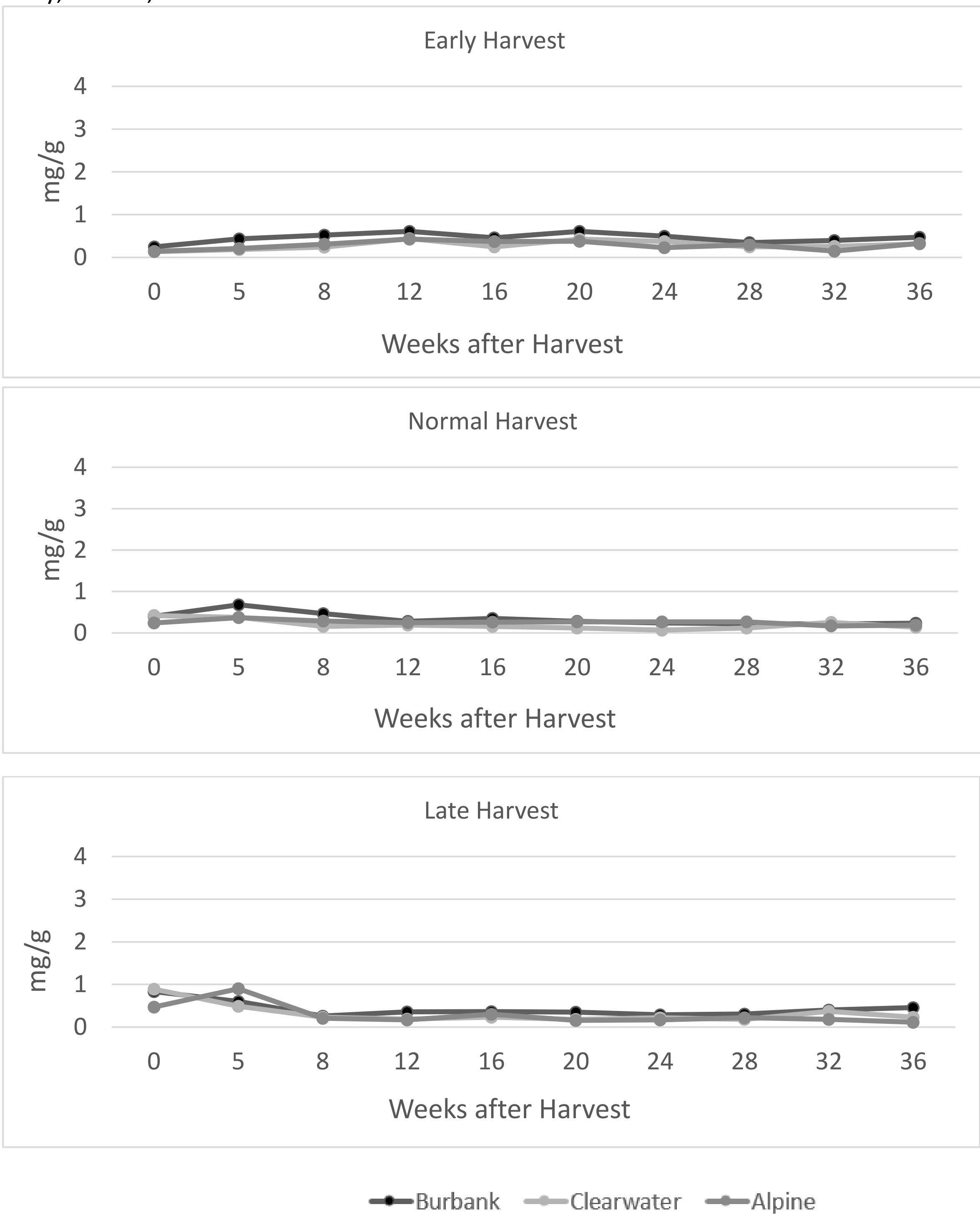


Figure 35. Sucrose levels (mg/g) of three processing varieties over 36 weeks of storage at 8.3°C; Russet Burbank, Clearwater Russet, and Alpine Russet, at three harvest timings; early, normal, and late in 2015.

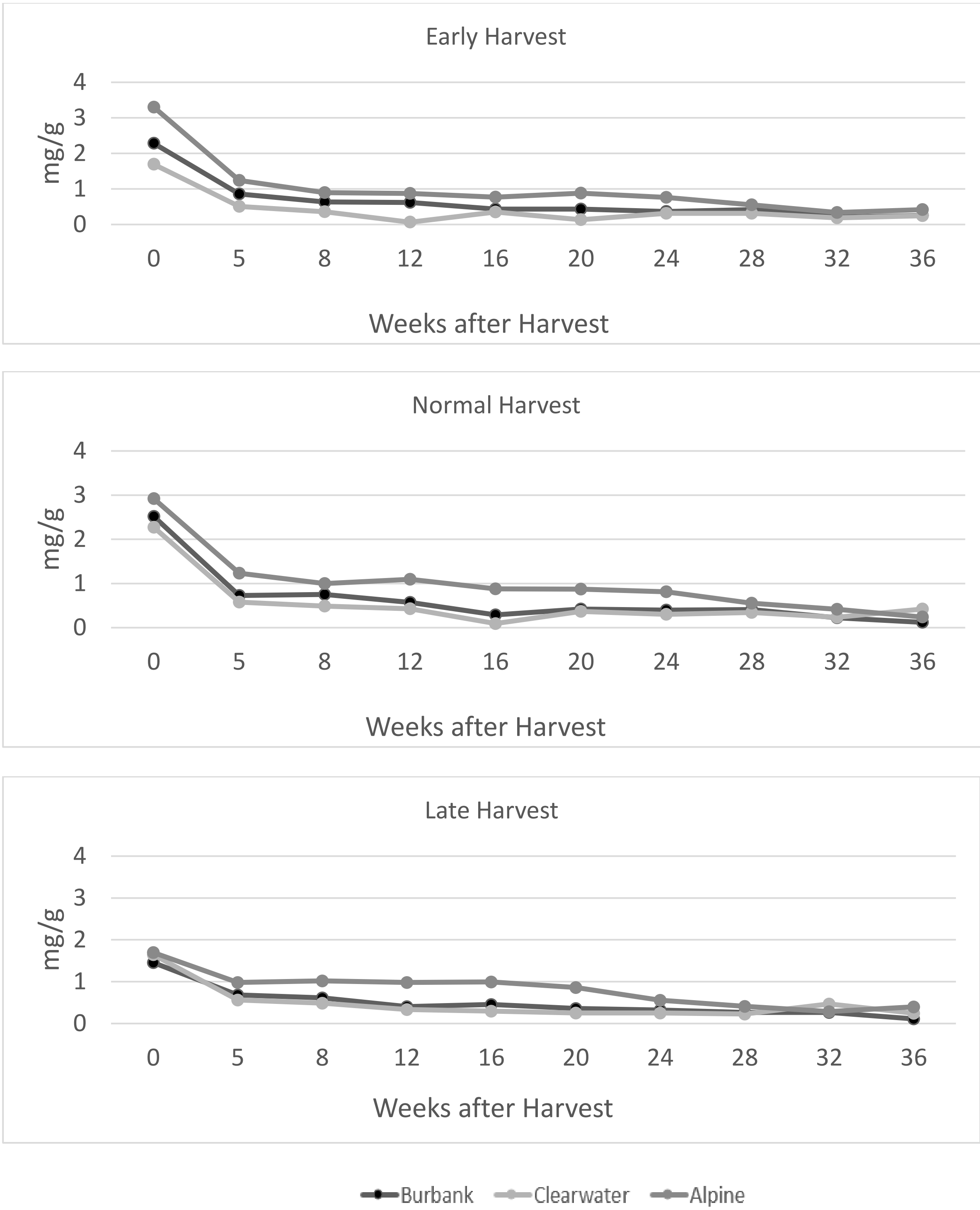


Figure 36. Sprout Index of three processing varieties over 9 months of storage at 8.3^{o}C; Russet Burbank, Clearwater Russet, and Alpine Russet, at three harvest timings; early, normal, and late in 2014. Scale of 0-40, adjusted to scale of 20 to show differences. 0=no sprouting, 5 = acceptable, 10= unacceptable

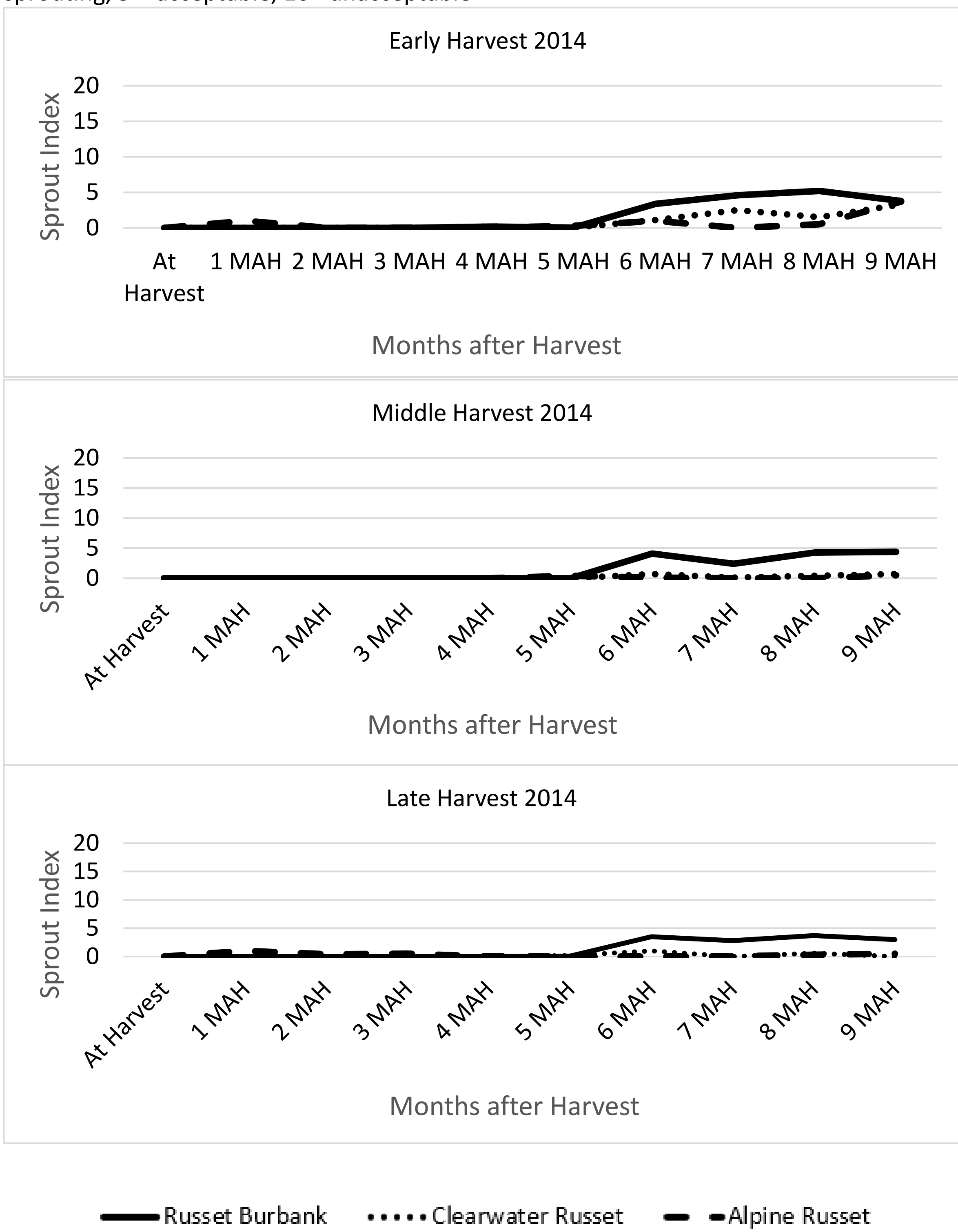
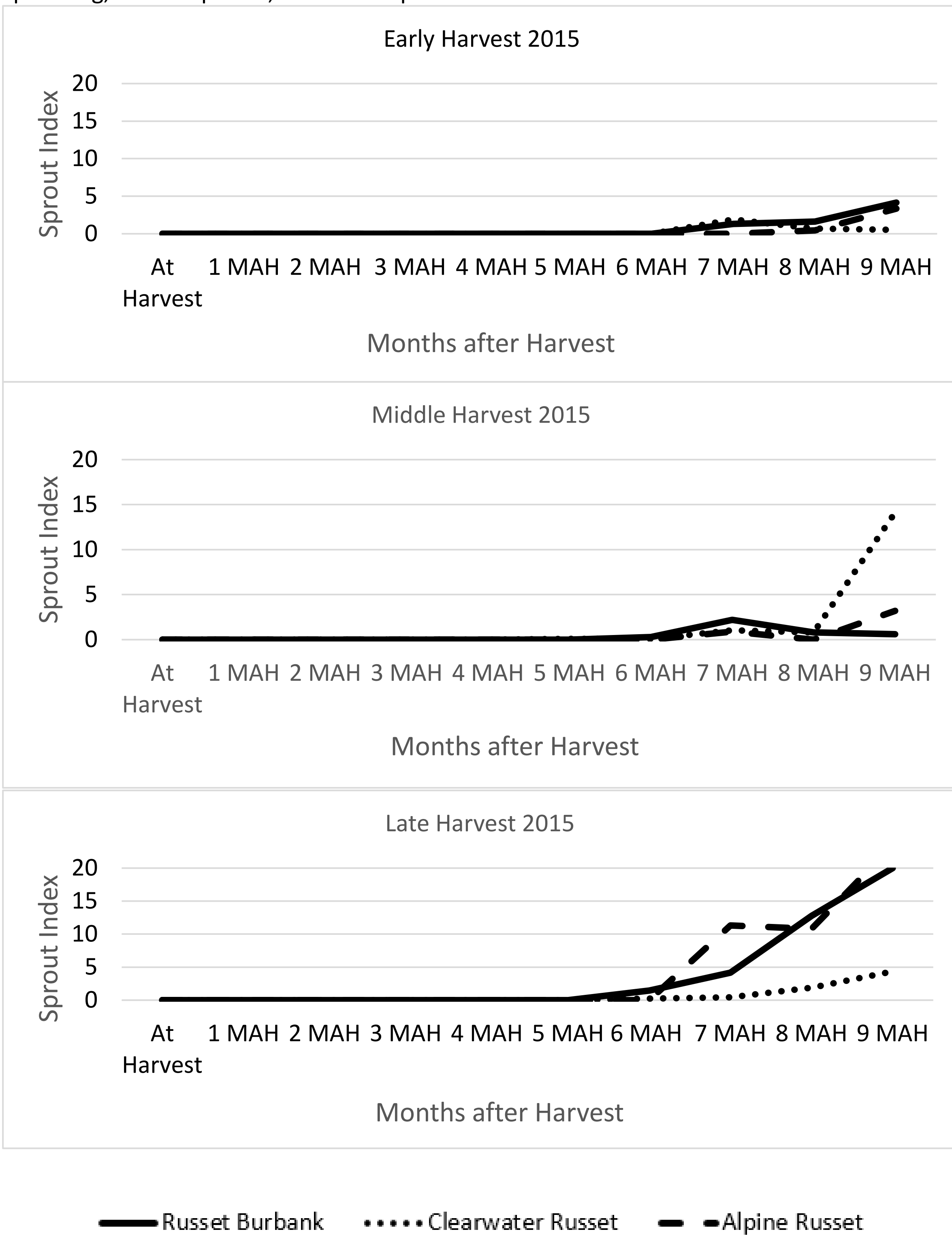


Figure 37. Sprout Index of three processing varieties over 9 months of storage at 8.3^{o}C; Russet Burbank, Clearwater Russet, and Alpine Russet, at three harvest timings; early, normal, and late in 2015. Scale of 0-40, adjusted to scale of 20 to show differences. 0=no sprouting, 5 = acceptable, 10= unacceptable



APPENDIX 1

EFFECT OF HARVEST DATE AND VARIETY ON POTENTIAL TO DISCOLOR DUE TO POLYPHENOL OXIDASE ACTIVITY

INTRODUCTION

Polyphenol oxidase is an enzyme found naturally within the potato tuber and is believed to aid in protecting the tuber from disease forming microbial invasion (Thygesen, Dry, & Robinson, 1995). The melanin that is formed from the enzymatic process is thought to provide a physical barrier to the advancement of the microbial infection (Busch, 1999). However, beneficial that action may be, the polyphenol oxidase reaction causes an undesirable discoloration within the flesh of the potato, resulting in quality issues and economic losses for the entire chain of distribution for potato products (Thornton & Bohl, 1995).

Polyphenols and polyphenol oxidase are found naturally within the potato cell, however, they remain compartmentalized within separate cellular structures thus restricting their interaction and discoloration (Busch, 1999). The polyphenol oxidase reaction typically occurs when the potato has been physically damaged by harvest operations or when exposed to prolonged pressure, as with long-term storage (Olsen & Thornton, 2010). The cell wall is then disrupted and the intercellular components interact to form quinone products, which interact further with cellular proteins via oxidation to form the blue-purple melanins associated with potato bruising (Thygesen, Dry, & Robinson, 1995). Studies have shown that potatoes with higher polyphenol oxidase content tend to have a higher degree of bruising (Mondy & Klein, 1961)

This study was conducted to determine the effect of harvest timing on the discoloration associated with melanin formation in three processing varieties; Russet Burbank, Clearwater Russet, and Alpine Russet. The study included a long-term storage evaluation of discoloration over a 9-month storage season. The intent of the study was to evaluate discoloration potential over time as an indirect indicator of the potential for subsequent graying of French fries made from the stored potatoes.

MATERIALS AND METHODS

The experiment was conducted in 2014 and 2015 at the University of Idaho Research and Extension Center at Parma, Idaho on Greenleaf silt loam soil. The experimental design was a split-plot randomized complete block design with four replications. The main plot treatments consisted of three separate harvest dates 1) early or prior to physiological maturity, 2) normal or at physiological maturity, 3) late or past physiological maturity. Maturity was determined by weekly senescence evaluations of the field. In 2014, this study was grown concurrently with a separate study that conducted periodic specific gravity measurements of Russet Burbank to estimate maturity. Those measurements aided this study in determining approximate maturity. Subplots were based upon variety, Russet Burbank, Clearwater Russet, and Alpine Russet.

Trial design and cultural management were described in Chapter 2. Monthly sampling for graying and discoloration began at harvest and continued thereafter until 9 months after harvest.

Also at 1 month after harvest, all tubers received an 8ppm CIPC treatment via hot fogging at 304^{o}C. At 1 week after treatment, a CIPC residue sample was taken by sampling 4 tubers from of each replication and sampled monthly thereafter. The tubers were sent to DiChlor Laboratories in Meridian, Idaho for analysis. In year 2015, an additional CIPC treatment was required and the chemical was applied at 8ppm.

At monthly sampling intervals, ten potatoes from each sample were washed and cut into 9.5mm French fry strips and divided into two piles. One pile was prepared for assessment of discoloration and used the center two strips of the potato. The other pile was prepared simultaneously for texture analysis by taking 4 strips from near the center of the potato. Both piles were blanched in their own pots at 80^{o}C for 6 minutes. The two piles were then hand dried separately on the counter top with paper towels, set onto individual metal baking racks, and dried for 3 minutes at 50^{o}C. The two piles were fried in their own baskets in a Wells F-49 Fryer using canola oil at 190^{o}C for 4 minutes. After frying, the strips were removed from the fryer and dumped into separate piles onto a paper towel covered counter. The strips set for 1 minute at room temperature and were fried in separate baskets a second time at 190^{o}C for 1 minute and 45 seconds. The strips from both baskets were dumped onto the paper towel covered countertop, still in their separate piles. Once the textural analysis was completed, the remaining fries were sliced open along the length of the fries and opened gently to reveal the interior of the French fry. The color was compared to a bruise chart for analysis of discoloration and scored on a scale of 1 to 10 (Figure 1). Concurrently, three potatoes from the monthly sampling were analyzed for discoloration using the methodology described by J. M. Busch, 1999. Four 5mm slices were cut with a knife across the short axis of each washed, but unpeeled potato. The slices were placed in Petri dishes and 100 microliters of control buffer (0.1 M Tris-HCL/0.02% *w/v* SDS, pH 9.0) was spread over the surface of the slices using a glass laboratory hockey stick. Substrate solution (100 microliters of 0.01 M disodium tyrosine/ 0.1 M Tris-HCL/0.02% *w/v* SDS, pH 9.0) is spread over the test slices. The lids were placed on the dishes to reduce evaporation. Slices were incubated for 1 hour at 30^{o}C and then examined for the black discoloration of melanin. The potatoes were assessed and graded using the same bruise color chart utilized for analyzing graying with the French fry strips.

Discoloration, i.e. graying, was scored on a scale of 1 to 9 with one corresponding to potato samples having no color discoloration and 9 corresponding to potato samples having the darkest of discoloration. When scoring for graying, French fry strips with low scores between 0 – 4 indicated that little to no graying had occurred whereas French fry strips with high scores between 5 - 9 indicated that the sample had significant graying. When analyzing for the melanin formation within the potato slices, scores of 0 - 4 indicated that discoloration was present and scores of 5 – 9 indicated that a significant level of discoloration was present.

RESULTS

During the nine month storage season, the monthly evaluation of the French fry strips did not reveal graying in color to any significant degree among the three harvest timings or three varieties (data not shown).

Differences in discoloration of fresh cut slices were not observed in regards to harvest timing. However differences were noted in regards to variety. In particular, Russet Burbank had significantly higher levels of discoloration at 5 months and 9 months after harvest in 2014 and at harvest, 5 months, and 9 months after harvest in 2015 than Alpine Russet or Clearwater Russet (Figure 1). The higher levels of discoloration found with Russet Burbank correlated to darker colors associated with bruising or graying than the lower levels observed with Alpine Russet or Clearwater Russet (Figure 2).

DISCUSSION AND CONCLUSIONS

The original purpose of the project was to ascertain whether higher discoloration scores corresponded to a higher incidence of graying within cooked French fry strips as effected by harvest timing. However, due to the lack of graying within the French fry samples over the storage season for both study years, the full scope of the study was not fully completed. Nevertheless, the information acquired from the testing did provide insight into the variable level of bruising and discoloration within the three different varieties used in this experiment. It is possible that this information on bruising could prove valuable when discussing the bruise potential of the three varieties studied in regards to processing end-product. The simple, non-toxic testing method that was used in this study could also be used to ascertain the bruising and graying potential of upcoming varieties as part of the variety breeding program.

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Mondy, N. I., & Klein, B.P. (1961). The interrelationships of potato discoloration, polyphenol oxidase activity, and nitrogen content of potatoes. *American Potato Journal,* 38(1), 14-21. Doi:10.1007/bf02861948

Olsen, N., & Thornton, M. (2010). *Harvest goal: maximize bruise-free potatoes*. Retrieved from College of Agriculture, University of Idaho website: https://www.uidaho.edu/cals/potatoes/press-releases-and-publications/maximize.bruise-free.potatoes-May-2010.ashx

Thornton, M., & Bohl, W. (1995). *Preventing potato bruise damage* (725). Retrieved from College of Agriculture, University of Idaho website: http://www.cals.uidaho.edu/edcomm/pdf/BUL/BUL0725.pdf

Thygesen, P. W., Dry, I. B., & Robinson, S.P. (1995). Polyphenol Oxidase in potato: A multigene family that exhibits differential expression pattern. *Plant Physiology,* 109(2), 525-531. Doi:10.1104/pp.109.2.525

Figure 38. Pressure bruise chart used to evaluate polyphenol oxidase content.

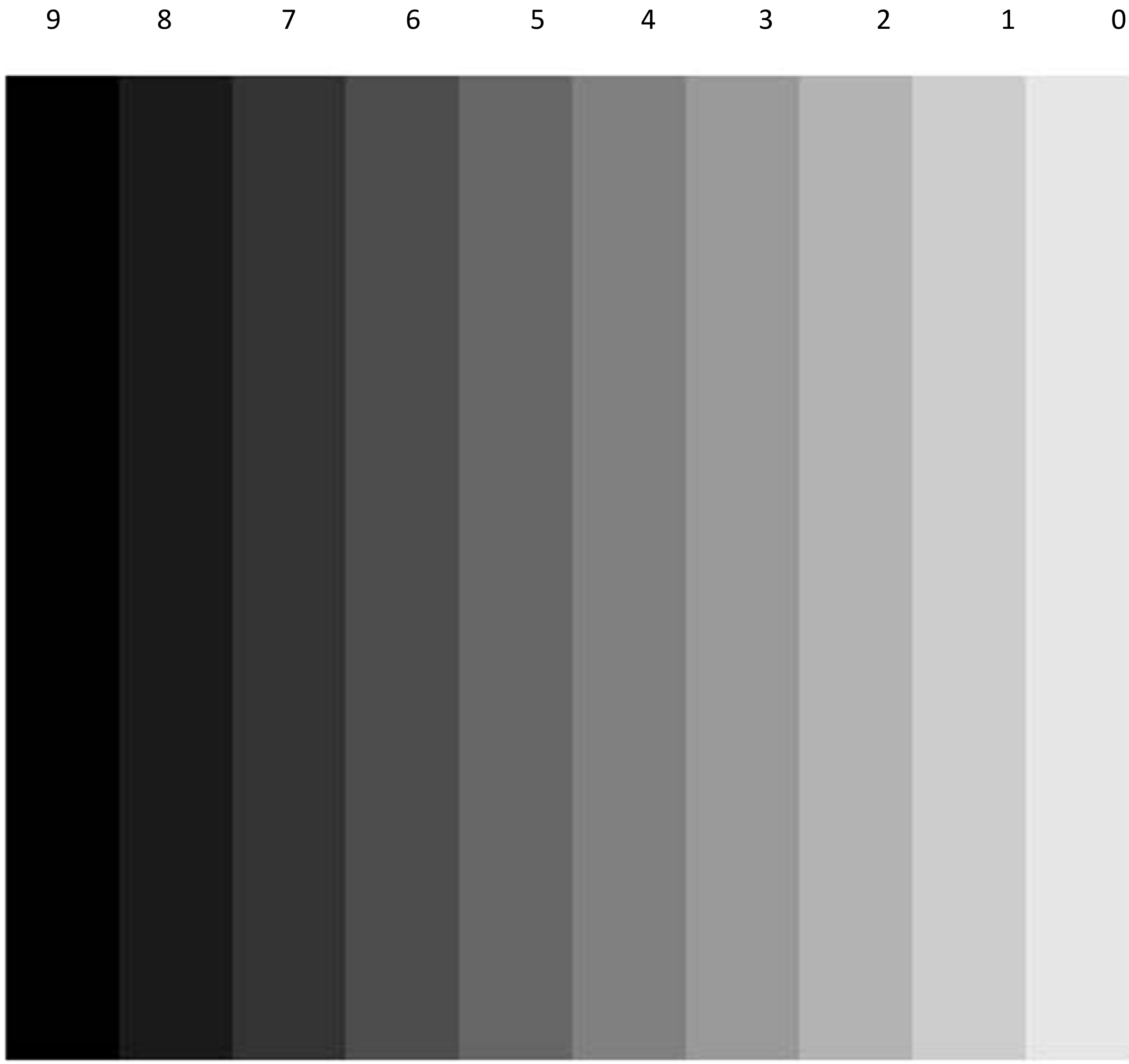
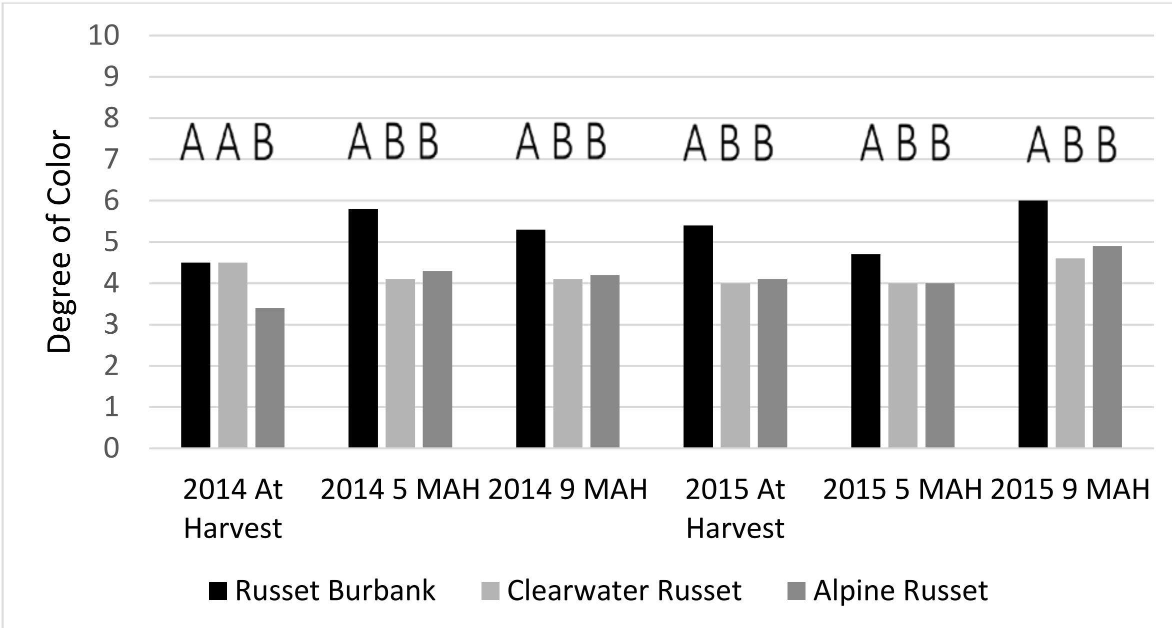
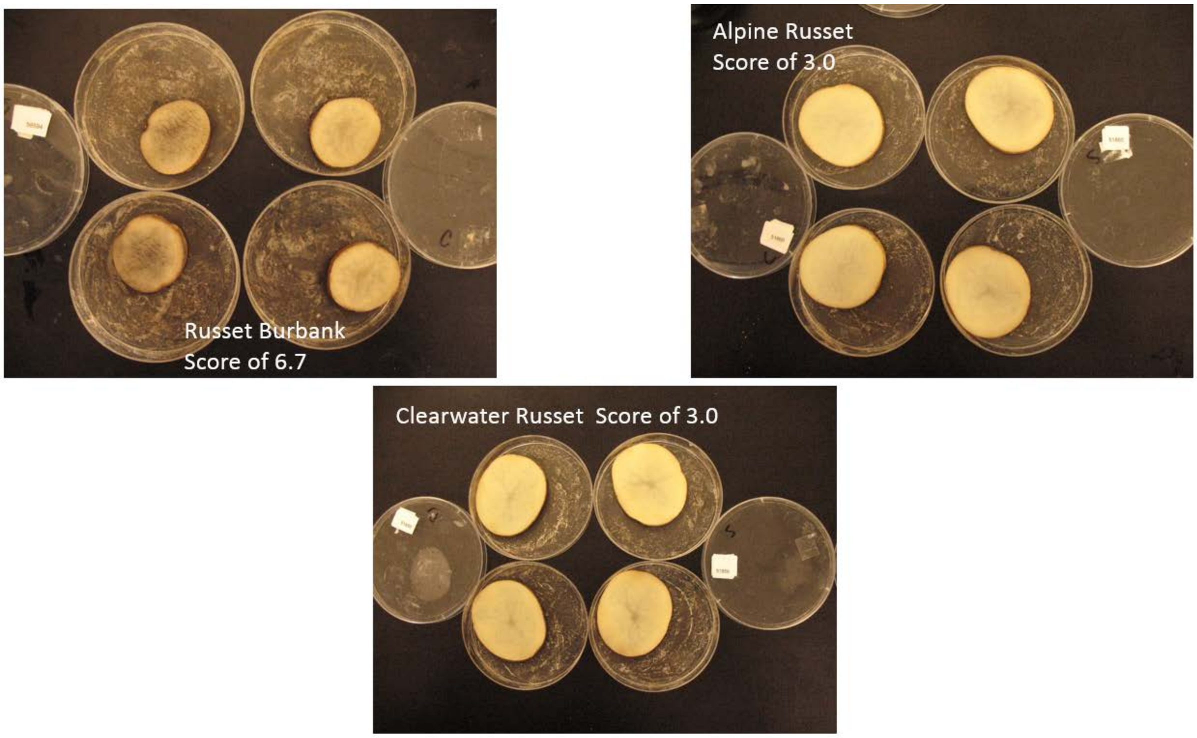


Figure 39. Effect of harvest timing and variety on the degree of discoloration for potatoes grown at Parma, ID during 2014 and 2015. Values are means of four replications.



5MAH = five months after harvest, 9MAH = nine months after harvest. From Figure 33: 0 = no discoloration, 1-2 = hint of discoloration, 3-4 = minor discoloration, 5-6 visible discoloration, 7-8 = strong discoloration, 9-10 = severe discoloration.
Means with same letter are not significantly different at $p<0.05$.

Figure 40. Example of discoloration associated with polyphenol oxidase content of three processing varieties, Russet Burbank, Clearwater Russet, and Alpine Russet.



APPENDIX 2

SAMPLE EXTRACTION OF CIPC AND DETERMINATION BY HPLC

DOCUMENT 500, REVISION R8, REPRINTED FROM DICHLOR ANALYTICAL LABORATORIES

1.0 PURPOSE

1.1 This document describes the methodology for the extraction of chloropropham from potato peels into reagent alcohol for High Performance Liquid Chromatography (HPLC) analysis.

2.0 EQUIPMENT

2.1 Varian Prostar liquid chromatography system (GLP Instrument No. 1).
2.1.1 Varian ProStar 335 Photo Diode Array Detector.
2.1.2 Varian ProStar 230 Solvent Delivery Module.
2.1.3 Varian ProStar 410 Autosampler
2.1.4 Varian Pursuit XRs 5u DP 250 x 4.6 mm analytical column or equivalent.
2.1.5 Varian Metaguard 4.6 mm Pursuit 5u DP guard column or equivalent.
2.1.6 Varian Galaxie Chromatography Data System Software.
2.2 2 ml vials with open screw caps fitted with Teflon lined silicone septa.
2.3 Analytical balance capable of 0.1 g accuracy.
2.4 Glass Pasteur pipettes.
2.5 Repipettor bottle top dispensers calibrated to deliver 50 ml aliquots.
2.6 Calibrated thermometer capable of reading 45 C.
2.7 Timer.
2.8 Paring knife or equivalent.
2.9 16mm x 100mm test tubes or equivalent.
2.10 Osterizer Blender or equivalent.
2.11 Electric Hot Plate.
2.12 Kitchen Stew Pot.
2.13 Thermolyne Roto Mix 51300 (with 180 revolutions/minute fixed rotation speed) or equivalent.
2.14 Non-coated Paper Plates.
2.15 Standard Kitchen Vegetable Peeler.
2.16 Screw Driver.
2.17 Regular Mouth Kerr Glass Pint Jars with plastic lid.
2.18 Whatman #2 filter paper or equivalent.
2.19 Glass Funnels.

3.0 REAGENTS

3.1 Fortified Standard Analytical Solution (FSAS) 80/20 prepared as per SOP 502 R3.
  3.1.1 HPLC grade reagent alcohol
  3.1.2 HPLC grade water
3.2 Calibration Standards prepared as per SOP 502 R3.
  3.2.1 FSAS 80/20 solution
  3.2.2 Barban
3.3 HPLC Eluent for CIPC analysis as per SOP 502 R3.
  3.3.1 HPLC grade acetonitrile
  3.3.2 HPLC grade water

4.0 PROCEDURE

4.1 Clean all glassware to be used as per SOP 201 R4.
4.2 Remove logged in samples from cooler.
4.3 Clean gloves are worn throughout sample preparation.
4.4 Record appropriate information in the Sample Log Book.
4.5 Four (4) potatoes from the sample storage bag are cut in half, taking two stem ends and two bud ends. One (1) half of each potato is placed on a tared paper plate. The remaining half is returned to the sample storage bag. This creates a composite sample equivalent to two (2) whole potatoes.
4.6 The tared plate and potato are placed on the balance.
4.7 The sample weight of the potatoes is taken and recorded in the Sample Log Book.
4.8 A small area at the end of the potatoes is peeled enough to allow for the insertion of a screw driver into the potato. The screw driver is used to hold the potato to reduce the amount of handling contamination.
4.9 The potatoes are peeled carefully onto the paper plate.
4.10 The peel sample is transferred to a glass Kerr pint jar and combined with 100 ml of FSAS 80/20. Record Bottle- top dispenser use in Equipment Use Log Book.
4.11 The sample is blended using the blender for approximately 30 seconds.
4.12 After blending, the peel sample is placed in the water bath that has been heated to 45°C ± 5°C. Record thermometer use in the Equipment Use Log Book.
4.13 The peel sample is allowed to set in the water bath for 15 minutes.
4.14 Following the water bath the sample is placed on the Rotomix and rotated for 15 minutes, followed by approximately 15 minutes resting at room temperature.
4.15 After 15 minutes when the sample has settled; approximately 15ml of sample solution is transferred to a double filtration apparatus using filter paper funneled into a test tube.

4.16 A 2ml aliquot of the filtered extract is placed into a 2ml auto sampler vial using a Pasteur pipette.
4.17 The sample is analyzed via HPLC as per SOP 499 R2 using the appropriate method in the Galaxie software.

5.0 SAMPLE ANALYSIS

5.1 Before starting the samples on the HPLC, monitor the baseline to ensure an even and steady baseline as per SOP 499 R2.
5.2 HPLC system is prepared with:
5.2.1 Varian Pursuit XRs 5u DP 250 x 4.6 mm column or equivalent.
5.2.2 Metaguard 4.6 mm Pursuit 5u DP guard column or equivalent.
5.2.3 The HPLC eluent for CIPC analysis as per SOP 502 R3.
5.2.4 Flow rate is 1.5 ml per min.
5.2.5 The detector wavelength is 240 nm.
5.2.6 The Galaxy Chromatography software is programmed to quantify chloropropham by the internal standard method.
5.3 Follow SOP 313 to set up sequences and start analysis using appropriate method.
5.4 If a shutdown method is used at the end of the sequence, no additional procedure should be necessary.
5.5 If no shutdown method is used:
5.5.1 Allow at least 10X the column volume of appropriate solvent to elude from the column.
5.5.2 Manually shut off the Varian ProStar 230 Solvent Delivery Module by putting module in Local mode and pressing Stop.
5.5.3 Make sure pump is no longer pumping solvent. It is not necessary to turn the pump off just stop pumping.
5.5.4 Turn off lamp in the Varian ProStar 335 Photo Diode Array Detector.

6.0 CALCULATIONS

6.1 Manual calculation of CIPC:

$$\frac{\text{(CIPC PA)}}{\text{(Barban PA)}} \times \frac{\text{(CIPC Response Factor)}}{\text{(Barban Response Factor)}} \times \text{(ug/ml Barban)} = \text{ug/ml CIPC in extract}$$

$$\frac{\text{(ug/ml CIPC in extract)(100 ml extract)}}{\text{(g potato)}} = \text{ug/g CIPC in potato}$$

6.2 Instrument calculation of CIPC:

6.2.1 Galaxie software determines peak area (PA) and uses response factor and Barban values from calibration curve data to calculate ug/ml CIPC in extract.

6.2.2 Enter “100” as the multiplier and “actual weight in grams of potato” as the divisor in the Varian Galaxie software sequence and read the ug/g directly from the results file.

7.0 QUALITY ASSURANCE

7.1 GENERAL

7.1.1 Residue testing of samples will incorporate two verification standards, CV2 and CV4. This will verify the accuracy of the equipment and subsequent analysis.

7.1.2 Verification standards will be run at the beginning and at the end of every sample run and also every 10 samples or more frequently if necessary to assure quality and bracket all samples.

7.1.3 Verification standards must be within +/- 10% of known value to be considered valid.

7.1.4 Analytical data between invalid standards are considered suspect, must not be reported and should be reanalyzed. All analytical data must be bracketed with valid verification standards to be considered valid.

Prepare calibration standards, prepare verification standards and determine calibration curve according to SOP 502 R3.

7.2 SPECIFIC

7.2.1 Open and review each chromatogram ensuring peak retention time and shape is consistent with Calibration Verification Standards.

7.2.2 Review the peak area for Barban to ensure it is consistent with historical data.

7.2.3 Check chromatogram baseline and reintegrate peak if necessary. Analyst will use their judgment for determining need for re-integration.

7.2.4 Check that divisor and multiplier are correct in software.

7.2.5 Record residue data results (in units of ug/g) into the Sample Log Book.

7.2.6 If the QC validates the data, report results to one decimal place.

7.2.7 The detection limit for method CIPC is 1.0 ppm CIPC. Values below 1.0 ppm will be reported as <1.0 ppm.

7.2.8 The detection limit for CIPC_LOW is 0.1 ppm. Values below 0.1 ppm will be reported as <0.1 ppm.

7.2.9 Because of the calculations used by the software, peak areas should be used to determine if the sample is within the linear range for the method. Samples with peak areas above the highest standard (regardless of the final value) will be diluted in FSAS 80/20 to bring the peak areas within the linear range and analyzed again. Calculate final result factoring in the dilution.

7.3 REPORTING

7.3.1 If the QC validates the data, report results to one decimal place, rounded as appropriate.

7.3.2 Enter results into the LID database.

7.3.3 A separate analyst reviews all raw data, results and customer information to make sure report is correct and enters their name in the “QC checked by” box on the LID report.

7.3.4 Report is saved to the appropriate location on the server and a hard copy is printed.

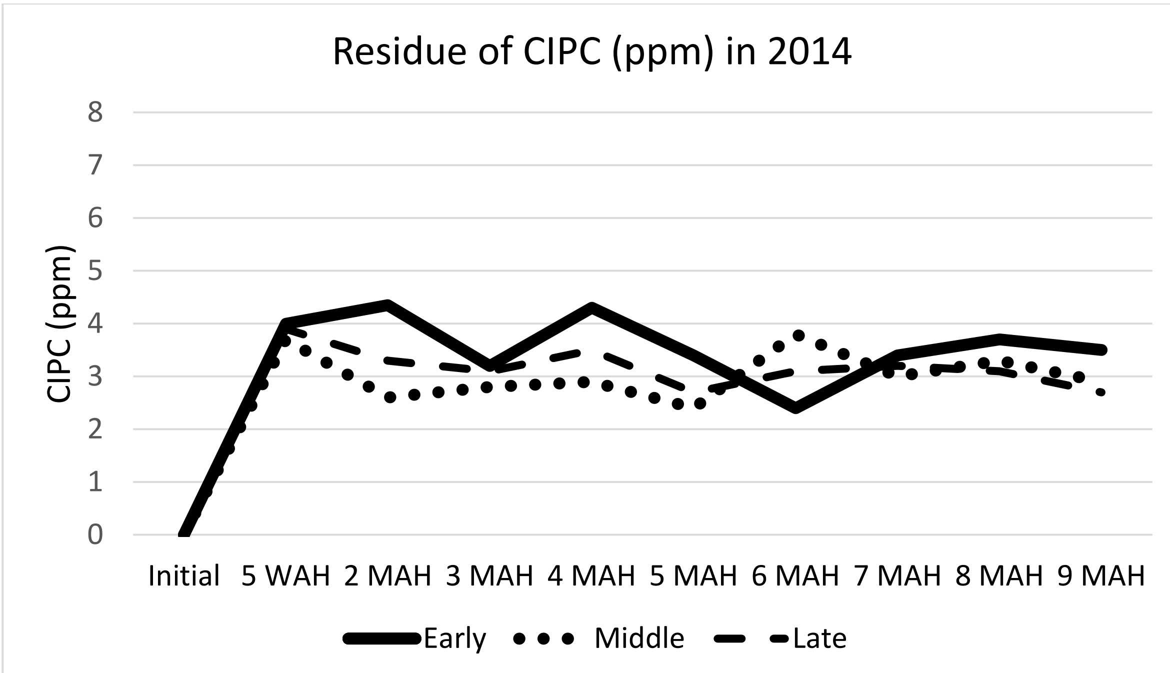
7.3.5 Report is emailed and/or Faxed to the customer.

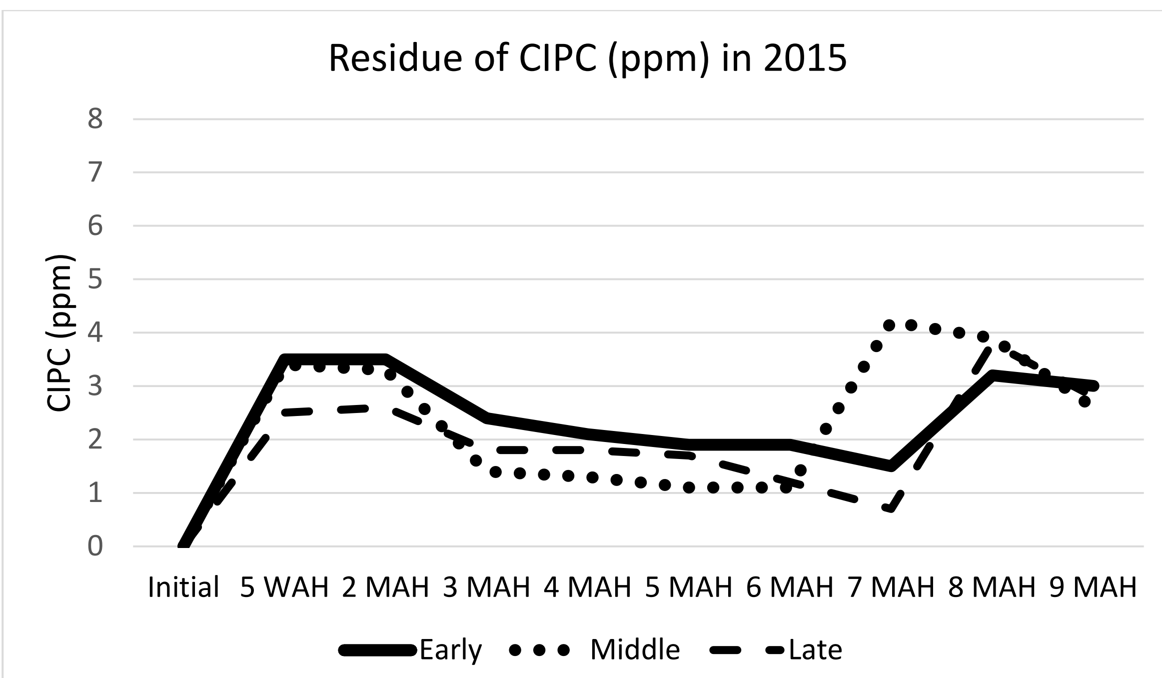
7.3.6 Report and all associated paperwork are submitted to Accounting for billing. A hard copy of the report is sent with the bill to the customer.

7.3.7 Report and all associated paperwork is returned to the lab and filed with the Archived Results.

APPENDIX 3

RESIDUE OF CIPC (ppm) OF EARLY, NORMAL, AND LATE HARVEST AVERAGE ACROSS THREE VARIETIES IN 2014 AND 2015.





APPENDIX 4

STANDARD OPERATING PROCEDURE: FRY COLOR ANALYSIS FOR RESEARCH SAMPLES

DOCUMENT #601, REVISION R1, REPRINTED FROM DICHLOR ANALYTICAL LABORATORIES

1.0 PURPOSE

1.1 This document provides guidelines for frying potato samples and evaluating fry color for research purposes. Number of dark ends and the degree of mottling is also rated.

2.0 EQUIPMENT

2.1 Wells model F-49 fryer or equivalent
2.2 Shaver Specialty Company potato slicer or equivalent
2.3 Cooking thermometer capable of measuring procedure temperatures
2.4 Analytical balance capable of 0.1 g accuracy
2.5 Potato peeler
2.6 Oven capable of drying samples

3.0 REAGENTS

3.1 Tap water for cleaning and blanching
3.2 Oil for frying

4.0 PROCEDURE

4.1 Select the 10 most uniform, least blemished tubers from the 12 tuber samples submitted.
4.2 Select the largest and smallest tubers from the 10 sample set and put aside.
4.3 Remove loose soil and debris from tubers; lightly wash under tap water and air dry.
4.4 Of the 8 remaining tubers, record the individual weights of the largest and the smallest tubers to obtain the weight distribution.
4.5 Peel stem-end (basal) side of all 10 potatoes. This will be used to differentiate basal and apical ends after frying.
4.6 Cut the tubers into 3/8” (1 cm) strips and collect 2 center cut strips that are the most defect free from each tuber. Discard the remaining strips. Repeat for remaining tubers combining the 20 center strips into the same colander.
4.7 Spray-wash the raw strips for 10-15 seconds with cold tap water to remove excess starch and potato juice.
4.8 Blanch strips in tap water at 175 °F (81 ºC) ± 5 °F for 7.0 minutes. Blot dry to remove moisture.
4.9 Place in strips on a baking sheet in a monolayer. Heat for 3.0 minutes at 180

°F (82 ºC) ± 5 °F.

4.10 Fry the combined 20 potato strip in pre-heated 375 ºF (190.5 ºC) ± 5 °F oil for 4.0 minutes.

4.11 Remove from fryer. Blot excess oil from fries and allow to sit for 1 minute

4.12 Fry the fries a second time in pre-heated 375 ºF ± 5 °F (190.5 ºC) for 1 minute and 45 seconds.

4.13 Blot excess oil from fries and allow to sit for approximately 3 minutes.

4.14 Score the average color of each individual fry using the USDA Color Standards for Frozen French Fried Potatoes (FSOP 601-A). Ignore color of outer ¼" end of fry. Record evaluation information on Fry Color Sheet (FSOP 601-B).

4.15 Record number of strips that have a darkened end (outer 1") that is USDA color 3 or higher.

4.16 Evaluate strips for degree of mottling: Unevenness in color due to variations in sugar content throughout the fry. When evaluating mottling, you do not score for darkness of color, but for unevenness of color. Also ignore color variations due to bruises or mechanical damage. Use the following numeric scale:

1: No mottling – Nice even color, no spots, no blotches, no marbling of darker and lighter colors. Note: score for unevenness of color, the fry could be totally white, totally yellow or totally brown.

2: Starting to see some mottling.

3: Mottling visible – uneven colors.

4: Heavy mottling – but can get worse.

5: Severe mottling – heavily marbled, blotched and/or spotted.

4.17 Take photographs of samples with sample number visible.

APPENDIX 5

STANDARD OPERATING PROCEDURE: SUGAR ANALYSIS IN POTATOES

DOCUMENT #900, REVISION R1, REPRINTED FROM DICHLOR ANALYTICAL LABORATORIES

1.0 PURPOSE

1.1 Standard Operating Procedure describing how to measure d-glucose (dextrose) and sucrose levels in potatoes using a 2700 YSI Biochemistry Analyzer.

2.0 SUMMARY

2.1 A minimum of five tubers are selected, peeled and cut into 1/8 pieces. A composite sample is made by using two 1/8 pieces from each tuber, one from the stem end and one from the bud end. Samples are blended in a YSI diluent buffer solution and a test tube is filled with the sample. After letting the sample cool in the refrigerator for at least one hour, the sample is measured on the YSI Biochemistry Analyzer.

3.0 EQUIPMENT

3.1 YSI 2700 Dual Channel Biochemistry Analyzer (GLP #41)
3.2 Analytical balance capable of measuring 0.1 grams
3.3 Analytical balance capable of measuring 0.01 grams
3.4 Sample Blender
3.5 Knife
3.6 Peeler
3.7 Grade A Graduated Cylinder appropriate for measure of 200 mL of liquid
3.8 Disposable Culture Tubes (10 x 75 mm)
3.9 Disposable Transfer Pipettes

4.0 REAGENTS

4.1 Diluent Buffer solution
4.2 D-glucose low standard
4.3 D-glucose high standard
4.4 Sucrose low standard
4.5 Sucrose high standard
4.6 Deionized grade water or better.
4.7 YSI 2357 -- YSI Buffer Concentrate
4.8 YSI 2363 -- Potassium Ferrocyanide Solution

4.9 YSI 2392 -- Sodium Chloride Solution

4.10 Store all reagents in refrigerator except buffer solutions: 4.1, 4.6

5.0 YSI SET-UP AND PREPARATION

5.1 Reagent Preparation

5.1.1 Diluent Buffer

5.1.1.1 Prepare Diluent Buffer by adding 40g/L NaH_2PO_4 and 10g/L Na_2HPO_4 in water (deionized grade or better) as per YSI publication #304.

5.1.1.2 Record solution information in the Diluent Solution Preparation Log (FSOP 900-A current revision) in the YSI Maintenance and Use Logbook.

5.1.2 Calibration Standards

5.1.2.1 Make four calibration standards, two sucrose and two d-glucose. Measure appropriate mass of standard on an analytical balance capable of measuring to 0.01 grams. Transfer source into a 100 mL class A volumetric flask and fill to volume with deionized grade water or better. Record mass, purity and final volume in the Standard Preparation Log (FSOP 900-E current revision). Calculate final concentration based on mass, volume and purity; record in the YSI Standard Preparation Log (FSOP 900-E current revision).

5.1.2.1.1 Example of final concentration calculation:

<u>0.20 g sucrose x 99.5% purity</u> X 1000 = 1990.0 mg/L sucrose

5.1.2.2 Low sucrose. Measure 0.2 g +/- 0.05 g sucrose for approximately 2000.0 mg/L sucrose standard. Calculate final concentration for later use.

5.1.2.3 High sucrose. Measure 0.5 g +/- 0.05 g sucrose for approximately 5000.0 mg/L sucrose standard. Calculate final concentration for later use.

5.1.2.4 Low d-glucose. Measure 0.1 g +/- 0.05 g d-glucose for approximately
1000.0 mg/L d-glucose standard. Calculate final concentration for later use.

5.2 Enzyme Membrane Installation *(YSI manual page 2-6).*

5.2.1 Unscrew the black probe retainer and gently pull the probe out of the block.

5.2.2 Remove the existing O-ring membrane assembly from the end of the probe. Be careful not to scratch the probe face.

5.2.3 Examine the probe surface and remove any pieces of membrane that remain.

5.2.4 Open a cavity of the YSI 2703 (Sucrose) plastic membrane holder and rinse the membrane inside with a few drops of salt solution (YSI 2392).

5.2.5 Place one drop of salt solution on the probe face.

5.2.6 Using the plastic membrane holder on the probe, press the O-ring membrane assembly gently onto the probe face.

5.2.7 Wipe off excess salt solution from the probe body and then return the probe to the sample chamber.

5.2.8 Finger-tighten the probe retainer so that the O-ring seals the probe in place. Do not over tighten.

5.2.9 Repeat this procedure for the white probe using the YSI 2365 (D-glucose) membrane.

5.2.10 When installing a new membrane, record information in the Enzyme Membrane Use Log (FSOP 900-B current revision) in the YSI Maintenance and Use Logbook.

5.3 Instrument Parameter Programming *(YSI manual page 2-15)*

5.3.1 This step will, usually, only need to be done on initial set up or if machine has been turned off and default parameters are restored. One exception is a change in the concentration of the sucrose or d-glucose standards whenever new ones are made.

5.3.2 Power up the YSI 2700.

5.3.3 From the MAIN MENU press [MENU].
Press [2] for SETUP.

5.3.4 Press [1] for GENERAL setup and enter date, date format and display contrast. All other parameters should be default. Press [0] to return to GENERAL setup.

5.3.5 Press [2] for MEASUREMENT PARAMETER SETUP and setup as follows:

5.3.5.1 Sample size: 45 uL

5.3.5.2 Sample station: #3

5.3.5.3 Calibration Method: Two stations

5.3.5.4 Black Probe**:** Chemistry: Sucrose, units: mg/L, Calibration Value: enter calculated low sucrose concentration from Standard Preparation Log (FSOP 900-E current revision), End point: 30 sec, Calibration station: 2

5.3.5.5 White Probe**:** Chemistry: d-glucose, units: mg/L, Calibration Value: enter calculated low d-glucose concentration from

Standard Preparation Log (FSOP 900-E current revision), End point: 30 sec, Calibration station: 1

5.3.5.6 Auto Calibration: Sample Error: on; Temperature: 1 C; Time: 15 min; Sample: 5; Cal shift: 2%

5.3.5.7 Press [0] to return to GENERAL setup menu. Press [0] again to return to SETUP menu.

RUN MODE SETUP:

5.4 Fluid System Priming *(YSI manual page 2-9)*

5.4.1 Reconstitute the buffer solution and transfer it to the Buffer Bottle. Empty the Waste Bottle.

5.4.2 From the MAIN MENU press [MENU] then press [1] for SERVICE.

5.4.3 Press [1] for Sipper. The sipper will home and should be centered over the large hole on the top of the sample chamber. If necessary, loosen the adjustment screw using the hex key and position the sipper. Retighten the adjustment screw. Press [1] to lower sipper for fine alignment. Make additional adjustments. Once the sipper is aligned over the sample chamber hole, press [1] to test sipper position. The sipper should not contact the stainless steel cone. After adjustment is complete press [0] to return to the SERVICE menu.

5.4.4 Press [2] for Buffer pump. The buffer pump will begin to prime the fluid system. Press [2] again if necessary to completely prime the buffer. The fluid system is completely primed when buffer flows from the steel cone at the top of the sample chamber.

5.4.5 Press [3] for Calibration pump. The calibrator pump will begin to pump calibration fluid through the calibrator line into the calibrator well. Press [3] again if necessary to completely prime the line. The fluid system is primed when calibrator fluid flows out of the tube in the calibration well.

5.4.6 Press [4] for Stir Speed. Adjust the speed until the stir bar jumps or is set to maximum. Press [0] to return to SERVICE menu. Press [0] again to return to the MAIN menu.

5.5 Probe Baseline Check *(YSI manual page 2-25)*

5.5.1 From the MAIN menu, press [MENU].

5.5.2 Press [3] for Diagnostic.

5.5.3 Press [3] for Probe.

5.5.4 Observe the probe current values. If they are above 6 nA, check to see if they are decreasing in value. You will need to allow an hour or more to establish stability when initially setting up the 2700 Select.

5.5.5 Check the sample chamber; it should be full of buffer. If necessary, press [1] for flush.

5.5.6 Once the baseline currents are below 6 nA and reasonably stable, press [MENU] to return to the main menu.

5.5.7 Record the final results of the probe values on FSOP 900-C current revision, YSI Setup Tests Log, in the YSI Maintenance and Use Logbook.

5.6 Membrane Integrity Test *(YSI manual page 3-7)*

5.6.1 A test tube filled with low sucrose calibration standard solution should be placed in the test tube holder at station #2. The low d-glucose calibration standard solution should be placed in the calibrator bottle at station #1.

5.6.2 Press [RUN] to put the instrument in run mode. The machine will perform a baseline check and calibrate itself to the two chemistries. When the unit is ready, the following display will appear "Ready to sample at Station #3". Press the [SAMPLE] button.

5.6.3 Use YSI 2363 Potassium Ferrocyanide (FCN) standard to determine if the membranes are structurally intact.

5.6.4 Pour a small amount of FCN standard (1000 mg/dL) into a test tube and run it as a sample at Station #3. Record the results of the membrane integrity test in FSOP 900-C current revision, YSI Setup Tests Log, in the YSI Maintenance and Use Log Book.

5.6.5 The maximum allowable values for FCN readings after calibrating with YSI standards are: D-Glucose (membrane 2365) = 50 mg/L Sucrose (membrane 2703) = 100 g/L

5.6.6 After a stable calibration with the recommended YSI calibration standard, FCN readings greater than the limit may indicate membrane structural failure. Recalibrate and repeat the FCN test. If readings are still high, refer to Section 8 in the YSI manual for Troubleshooting.

5.7 Linearity Test *(YSI manual page 3-8)*

5.7.1 Use the appropriate YSI linearity standard to test the linear range of the chemistries.

5.7.2 Place the instrument in [RUN] mode. When the unit is ready the following display will appear "Ready to sample at Station #3".

5.7.3 Pour a small amount of high sucrose standard into a test tube and run it at station #3. Record the linearity test results on FSOP 900-C current revision, YSI Setup Tests Log, in the YSI Maintenance and Use Logbook.

5.7.4 Acceptable linearity values for standards are +/- 5% of the calculated value from FSOP 900-E current revision.

5.7.5 Repeat the procedure for the high d-glucose standard.
If any reading is outside of the specified tolerance limits, recalibrate by pressing the [CALIBRATE] button and repeat the linearity test. If the reading is still outside of tolerance, refer to Section 8 in the YSI

6.0 SAMPLE PREPARATION PROCEDURE

6.1 Sample Preparation

6.1.1 Select 5 tubers per sample.

6.1.2 Peel each tuber and wash and dry with a paper towel.

6.1.3 Cut each tuber lengthwise in half and then lengthwise again into quarters. Cut all quarters in half again to make 8 pieces.

6.1.4 Remove one section from the stem end and one section from the bud end from each of the five tubers.

6.1.5 Weigh all sections from the sample to obtain a minimum weight of 300 g. Additional sections may be added to the sample, in sets of 2 (1 bud and 1 stem) to obtain the minimum weight. Record sample weight in the Sample Logbook.

6.2 Sample Blending

6.2.1 Place all sections into sample blender along with 200 mL of YSI Diluent solution.

6.2.2 Blend on liquefy speed until the sample is homogenous and liquefied, approximately 2 minutes.

6.2.3 Allow to sit for at least 2 minutes to allow separation of layers.

6.2.4 Using a disposable transfer pipette, transfer enough solution from the liquid layer (not foam) into a disposable culture tube and label accordingly.

6.2.5 Place parafilm over the culture tube and place in a refrigerator (4 °C) for at least 1 hour before sampling. For best results, run samples on the same day as preparation. If this is not possible, the liquid samples may be stored for up to 36 hours in a refrigerator.

7.0 SAMPLE INJECTION

7.1 Remove sample from the refrigerator, remove parafilm.

7.2 Once the machine is ready to sample, hit [SAMPLE].

7.3 Sipper arm will move to the #3 position and prompt for the sample, do not put the test tube at station #3 until the sipper arm has come to rest, or an error will occur.

7.4 Once the sipper arm is at rest, move the test tube into the #3 position, assuring that the sipper arm is about 1 inch into the solution (not foam). Press [SAMPLE] button.

7.5 The machine will draw up the sample and move to the sample well for injection.

7.6 Note: If the sipper arm retains an excessive amount of foam or sample on the outside area, it may affect the calibration of the machine and an error may occur. Clean the outside of the sipper arm with a kimwipe, clear the machine error and enter [RUN] mode again.

7.7 Machine will print out results for both chemistries.

7.8 The machine will self calibrate every 15 minutes, in which time you will not be able to sample.

7.9 Once all samples are finished, place the machine in [STANDBY] mode.

7.10 Record sample information in the Sample Logbook, and machine use in the YSI Machine Use Log (FSOP 900-D current revision), in the YSI Maintenance and Use Logbook.

8.0 CALCULATION OF RESULTS

8.1 Report sucrose and d-glucose results in milligrams of sugar per gram of potato (mg/g).

8.2 Calculate the mg/g results by using the YSI results (mg/L), the volume of diluent used to blend the sample (L) and the sample weight (g).

Example: $\frac{\text{3500 mg/L sucrose} \times \text{0.20 L}}{\text{300 g sample}} = \text{2.33 mg/g}$

8.3 Enter the sucrose and d-glucose results (mg/g) into the LID database. Retain the machine printout for QC purposes.

9.0 QUALITY REPORTING

9.1 Reporting

9.1.1 If the QC validates the data, report results as mg/g to two decimal places, rounded as appropriate.

9.1.2 Enter results into the LID database.

9.1.3 A separate analyst reviews all raw data, results and customer information to make sure report is correct and enters their name in the “QC checked by” box on the LID report.

9.1.4 Report is saved to the appropriate location on the server and a hard copy is printed.

9.1.5 Report is emailed and/or Faxed to the customer.

9.1.6 Report and all associated paperwork are submitted to Accounting for billing. A hard copy of the report is sent with the bill to the customer.

9.1.7 Report and all associated paperwork is returned to the lab and filed with the Archived Results.

APPENDIX 6

CALCULATION OF SPROUT INDEX

Sprout Index Data Collection Table														
STUDY:														
Observer														
				Peeping	white sprout tip visible in 2 or more eyes									
				Sprouts	>2mm									
	Date	Trt	Rep		Tuber 1									
					1	2	3	4	5	6	7	8	9	10
Treatment				Peeping Y/N										
Temp:				#eyes sprouting (>2mm)										
%RH:				longest sprout length (mm)										
Treatment				Peeping Y/N										
Temp:				#eyes sprouting (>2mm)										
%RH:				longest sprout length (mm)										
Treatment				Peeping Y/N										
Temp:				#eyes sprouting (>2mm)										
%RH:				longest sprout length (mm)										
Treatment				Peeping Y/N										
Temp:				#eyes sprouting (>2mm)										
%RH:				longest sprout length (mm)										

Apply the data collected above to the following equation to acquire the sprout index:

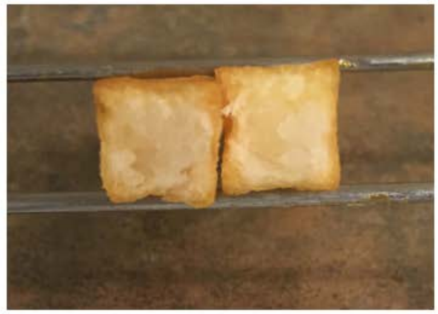
[(%N x 0.0) + (%A x 2) + (%B x 6) + (%C x 15) + (%D x 40)]/100

N – Not sprouted, A – 2mm, B – 2.1 to 10mm, C – 10.1 to 20mm, D – 20.1mm

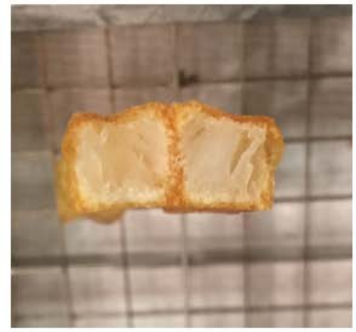
APPENDIX 7

APPEARANCE OF FRENCH FRIES

Raw Interior Score 3



Fluffy Interior Score 5



Hollowing Score 6

Additional hollowing Score 7

Extensive hollowing Score 8

Limp fry

Bend-over fry