Factors that Contribute to Bruise Development and Loss of Potato Quality

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Rabecka L. Hendricks

Major Professor: Nora Olsen, Ph.D.
Committee Members: Michael Thornton, Ph.D.; Patrick Hatzenbuehler, Ph.D.
Department Administrator: Juliet M. Marshall, Ph.D.

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Authorization to Submit Thesis

This thesis of Rabecka L. Hendricks submitted for the degree of Master of Science with a Major in Plant Science and titled "Factors that Contribute to Bruise Development and Loss of Potato Quality," has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

Major Professor:	______________________________________ Nora Olsen, Ph.D.	Date: ___________
Committee Members:	______________________________________ Michael Thornton, Ph.D.	Date: ___________
	______________________________________ Patrick Hatzenbuehler, Ph.D.	Date: ___________
Department Administrator:	______________________________________ Juliet M. Marshall, Ph.D.	Date: ___________

Abstract

Potatoes are extensively handled in the post-harvest chain from harvest in the field until reaching the ultimate consumer. This potato journey includes harvesting, handling in and out of storage, moving through packing sheds or processing facilities, being transported between locations, and finally reaching the consumer. Each time potatoes are handled, the potential for physical damage is heightened, which can result in blackspot and shatter bruises and lower quality. The overall goal of this research was to determine factors that contribute to bruise development and susceptibility and loss of potato quality within the post-harvest chain. To accomplish this goal, four major objectives were conducted in this project. The first objective was to determine how time in storage contributes to bruise development and susceptibility. The second objective was to evaluate the progression of bruise development within 24 hours and if fresh bruises identified up to five hours after impact are a reliable indicator of total bruise development commonly evaluated 24 hours post impact. The third objective was to examine bruise susceptibility of six cultivars impacted by a standard weight at three different drop heights. The final objective was to examine the bruise potential in packaged potatoes at a fresh pack facility.

Bruise development and susceptibility were determined using a 100 g weight to deliver uniform impacts on tubers. Evaluations for blackspot and shatter bruise variables were carried out on common russet cultivars including Russet Burbank, Russet Norkotah, Ranger Russet, Clearwater Russet, Teton Russet, Dakota Russet and Umatilla Russet between the first three objectives. Objective four utilized an impact recording device that measured peak accelerations experienced when packaged potatoes were dropped from various heights and onto different impact surfaces.

Key outcomes from this project are as follows. When tubers were bruised at harvest, the incidence of blackspot bruise increased within the first month of storage but afterwards remained at similar levels for the remaining months examined (eight months). Physical impacts at harvest resulting in shatter bruise showed no further development in storage. Potatoes physically impacted once removed from storage, showed a slight increase in blackspot bruise susceptibility over time, whereas shatter bruise susceptibility decreased the longer potatoes were held in storage. Looking at susceptibility of a single tuber, the risk of shatter bruise was greater near the bud end of the tuber, whereas the risk of blackspot bruise increased with proximity to the stem end. The shoulder location of a russet potato had higher bruise susceptibility compared to the flat surface indicating curvature of the tuber has a role in bruise susceptibility. The development of a bruise was evident within just a few hours of a 24-hour period after a physical impact occurred. The bruise color changed from a pink to brown discoloration primarily one to three hours after impact, and the incidence of pink discoloration declined rapidly after that time. Over 70% of the total blackspot bruise incidence was observed after four hours depending upon force of impact and cultivar. The majority (70%) of total bruise depth was developed five hours after impact. Significant differences in blackspot and shatter bruise susceptibility were seen between cultivars at different impact heights. Clearwater Russet and Dakota Russet had the highest blackspot bruise incidence compared to other cultivars examined. Teton Russet had the lowest blackspot bruise incidence, severity rating and depth examined between the cultivars but had the highest shatter bruise incidence. Dakota Russet had low susceptibility to shatter bruise at all impact heights examined. When boxed potatoes were dropped on to concrete or a plastic slip, the potatoes on the bottom of the box would have the highest risk of damage. The risk for damage was lower for potatoes in the top or middle of the box. When drop heights were lowered, or when cushioning material was added to hard impact surfaces (wooden pallet), the risk for impact damage was decreased throughout the box. When palletizing boxed potatoes, the risk of bruise decreased after the first layer was stacked on the pallet. The risk of high peak accelerations (over 100 g) was not seen in the dropped or stationary bales for any of the drop heights examined. Increased cushion for the bottom stack of potatoes during palletization in fresh pack facilities could lower the risk of bruise. Innovation of cushioned plastic slips could provide an economical and efficient alternative to wooden pallets. The overall project provided information for the industry to make decisions about how to manage for bruise at harvest, in storage, unloading, and in fresh pack and processing facilities.

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Dedication

I would like to dedicate this thesis to my husband, Noah Hendricks, for his patience when I was stressed, encouragement to push myself, and loving support throughout the many hours spent completing this project. I would also like to dedicate this thesis to my family, friends, and mentors throughout my life who provided the foundation to allow me to succeed and drowned out the voice of self-doubt. Words cannot express how grateful I am.

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Chapter 1: Introduction

Potatoes (*Solanum tuberosum* L.), a major horticultural crop in the United States, rely on quality standards to maximize efficiency and inputs, satisfy expectations, meet food safety requirements, and minimize food waste. In 2018, the potato crop had a combined value of over $2 billion in Idaho, Oregon, and Washington—three of the major potato producing states that supply 60% of all of U.S. production (USDA 2019). Idaho alone produced 31.5% of all U.S. production of potatoes in 2018 (USDA 2019). Agronomic inputs and management are aligned to grow quality potatoes that have minimal defects, but improper handling through the post-harvest handling operation chain can lead to sub-optimal quality. This sub-optimal quality can be noted during frequent crop inspections that occur as the harvested crop travels from the farm to consumer. Mechanical damage of tubers from major and minor physical impacts can result in potato bruises as a potato is handled (Figure 1-1). These physical impacts occur when tubers contact equipment components, as tubers change direction, or drop from conveyor belts onto different surfaces during harvest and handling operations (Bentini et al. 2006; Hyde et al. 1988).

Two major types of impact injury are blackspot bruise and shatter bruise. Blackspot bruising occurs when a tuber's cell membranes are damaged, but the skin is unbroken. The intracellular membranes rupture causing a biochemical reaction to occur between polyphenol oxidase (PPO), tyrosine, and other substrates, resulting in melanin formation that appears as a dark discoloration at the area of impact (Edgell et al. 1998; Vreugdenhil et al. 2007; Dean 1996). Shatter bruises split the cell walls of the damaged area and expand outward and deep into the tissue, resulting in large cuts and visible splitting of the skin (Vreugdenhil et al. 2007; Hollingshead et al. 2020a), as well as creating storability issues (McGarry et al. 1996) and entry points for pathogen infections (Singh et al. 2021).

Potato bruises can be economically damaging, because bruise-related quality issues can cause retailers and consumers to decide to not purchase or consume potatoes. In 1995, potato bruises were estimated to cost the U.S. potato industry $298 million (Thornton and Bohl 1995). Reducing bruise one percentage was estimated to save growers $3 million annually in 1992 (Hyde et al. 1992); which computes to $5.6 million today factoring for inflation. From 1984 to 2019 average U.S. potato yields increased by 19,503 kilograms per hectare and equaled 47,636 kilograms per hectare in 2019 (USDA 1999; USDA 2020). This increase in production has demanded the ability for handling operations to move a greater volume of potatoes in the same timeframe each year. Advances in harvesting technology have helped handle this increase in potato production, but the interval to successfully harvest potatoes remains the same. Potential for bruise is heightened solely from the number of potatoes being harvested and handled throughout the post-harvest chain.

One way to minimize blackspot and shatter bruise is to monitor harvest and handling equipment and take tuber samples to assess for damage in areas of high bruise probability. Bruise monitoring during handling operations can establish whether modifications to equipment or tuber conditions need to be made to minimize bruising. Blackspot bruise is difficult to assess because the discoloration takes time to develop. It has been shown that discoloration of blackspot bruise, beginning as a pink color, can be seen three to six hours after impact (Weaver et al. 1970). Laerke et al. (2002a) found blended tuber tissue samples develop pigment within 30 minutes, concluding blackspot bruise discoloration had the potential to develop in a short period of time. Thornton et al. (1973) also stated discoloration began six to 12 hours after impact and peaked at 24 hours, though the authors still recommended waiting six to 48 hours before assessing fully developed blackspot bruise levels from a sample. The United States Department of Agriculture (USDA) fresh market and processing inspection guidelines specify holding potatoes for 48 hours before any bruise inspections can be made to ensure full development of bruises (USDA 2012; USDA 2015). Multiple research studies have shown that adjusting the holding temperature after impact can influence the time required for blackspot bruise development to occur. Warmer temperatures (up to 32.2°C) can reduce blackspot bruise development time from 48 hours to 6 hours after impact (Olsen and Thornton 2017). Thornton (1982) held impacted tubers at 35°C for 6 hours and determined that 80% of blackspot bruises began to develop by this time.

From initiation (harvesting out of the ground) to completion of a handling operation, potatoes flow uninterrupted. Due to the time needed for blackspot bruises to develop knowledge of bruise levels and adjustments to lower those levels cannot occur simultaneously. Rapid bruise detection methods have been examined to shorten the gap between taking samples, evaluating for bruise, and adjusting equipment or conditions (Thornton 1982; Beaver and DeVoy 1986; McRae and Melrose 1993; Olsen and Thornton 2017). Commercial ‘hot boxes’ have been used to accelerate blackspot bruise development for a 12-hour detection method (McRae and Melrose 1993). To easily detect shatter bruise, dye solutions have been used to improve the visibility of the bruise (Hollingshead, et al. 2020b; Beaver and DeVoy 1986; McRae and Melrose 1993). Beaver and DeVoy (1986) concluded colder dye solution temperatures resulted in 15-to-30-minute longer time for shatter bruise detection. This study implied that at colder tuber pulp temperatures, development may be slower for both blackspot and shatter bruise. Developing bruise detection methods that minimize the lag in time between taking samples and having the necessary information to adjust equipment and conditions could help the industry reduce the potential for blackspot and shatter bruise at each step of the potato post-harvest chain.

After harvest, most of the potato crop is placed into storage to keep supply available until a new crop can be harvested. Growers have raised the question if bruises sustained at harvest can develop into more severe bruises, stay the same, or lower in severity while in storage. Previous research has reported conflicting information about how bruises sustained at harvest develop in storage. Skrobacki et al. (1989) found that, depending on impact force, blackspot bruise severity could increase or decrease 6 months into storage. Shatter bruise incidence was found to decrease throughout time in storage (Skrobacki et al. 1989). Ophuis et al. (1958) determined as potatoes sprouted in storage, the risk of blackspot bruise discoloration increased. There is a gap in knowledge regarding bruise development in storage since most of the previous research did not hold tubers impacted at harvest for long periods of time in storage. Examining bruises sustained at harvest throughout storage could help answer questions about how tubers respond to damaging impacts over time in storage.

The risk of mechanical injury does not end once tubers are placed into storage, so understanding the susceptibly to bruise damage at the time of removal is important. Laerke et al. (2002b) examined tubers every two months in storage and found both blackspot and shatter bruise severity decreased from harvest to 180 days in storage, although the rate of decrease in severity was dependent on cultivar. Dean et al. (1993) impacted tubers at four different times during storage (one to eight months) and found blackspot bruise susceptibility decreased in storage. Edgell et al. (1998) using an impact device, found bruise formation occurred more often at six months in storage compared to three months in storage. During storage, changes in tuber characteristics can include dehydration, age, and biochemical constituents—all of which have been recognized to potentially alter bruise susceptibility (e.g., Shetty et al. 1998; Sawyer and Collin 1960; Praeger et al. 2009). To minimize bruise when removing tubers from storage, it is crucial to understand the risk associated with handling tubers at this time.

Once potatoes are harvested and/or removed from storage, they are transported to a fresh packing or processing facility, known as the supplier (Figure 1-1). Suppliers prepare and package potatoes delivered by growers and then transport the packaged potatoes to their customer, the retailer. There is still a risk of damage through this part of the post-harvest chain because potatoes are being handled multiple times. Thornton and Davidson (1987) concluded potatoes handled throughout a fresh pack operation showed a 15% increase in bruise from storage and transporting via truck compared to when potatoes initially reached the fresh pack facility. An additional 20% increase in bruise was measured in potatoes once they reached the packaging stage in the facility.

A tool used for assessing physical damage and bruise potential or risk during handling is an instrumented sphere or impact recording device (IRD; Praeger et al. 2013). IRDs can be used in post-harvest operations to measure and record the acceleration of an impact and mimic how a potato (or another commodity) could potentially be impacted. IRDs can record peak acceleration, velocity change, number of impacts endured, and a time stamp for each data point, although not all models include velocity change (Hollingshead et al. 2020b). They are commonly used in harvest operations to indicate equipment that may need adjusting. IRDs can also be run through fresh pack facilities to measure physical impacts that can occur beyond what is seen at harvest (Klug et al. 1989). Once potatoes are packaged, there is less bulk handling involved and IRDs are not commonly used for assessment at this stage. Smaller packaged or bagged potatoes are collectively put together to form a larger packaged unit of a box or bale. Once packaged into paper bales or bulk cardboard boxes, potatoes must be palletized prior to transportation. Operations can use manual labor at this stage or have automated or robotic machinery that stack boxes or paper bales weighing up to 22.7 kg onto pallets. The boxes often hold loose potatoes whereas baled packaging includes 2.3 or 4.5 kg individually bagged potatoes. Examining contribution to bruise and quality issues prior to transit could help explain quality issues found in packaged potatoes when inspected at distribution centers. Previous research examined simulated transportation equipment and concluded shatter bruise can be caused by rough handling of packaged potatoes (Turczyn et al. 1986). Pason et al. (1990) used an IRD in apple shipments to examine potential damage that occurred during transit, although packaged apples were not intentionally dropped. Most research with IRDs has involved placing them on operating equipment, whereas Pason et al. (1990) provided context and validity for using an IRD in packaged containers rather than on equipment.

There are no standard techniques for determining bruise susceptibility. This makes comparative tests aimed at determining susceptibility among cultivars or evaluation of other variables (such as impact force or temperature) difficult (Opara and Pathare 2014). Methods of evaluating for bruise susceptibility include collecting sample tubers from harvesting operations (Misener et al. 1989; Canneyt et al. 2004), pouring tubers onto shaking tables (Laerke et al. 2002b), using falling impact/bolt devices (Corsini et al. 1999; Maas 1966; Thornton 1982; Stevens and Davelaar 1997; Kunkel et al. 1986; Laerke et al. 2002a), dropping tubers on to different surfaces (Bajema and Hyde 1998), or examining cellular compounds with in potato tissues (Linn and Pitt 1986). Bajema and Hyde (1998) noted that a smaller mass being dropped on to a tuber (falling impact device) will need more force to equate to the same impact force as a tuber dropping on to a surface. Pavek et al. (1985) found a high correlation between impact tests and enzymatic discoloration and concluded abrasive peeling could be used to screen for bruise resistance instead of impact tests. Overall, an impact device is a consistent method to examine bruise susceptibility over multiple cultivars and varying environmental circumstances because it removes variability associated with the size and shape of tuber (Mass 1966; McGarry et al. 1996; Kunkel et al. 1986). In addition to the diversity in methods of impacting a tuber to assess bruise susceptibility, there are multiple standards regarding the location on an individual tuber to direct the impact. Due to the diversity in techniques used in determining potato bruise susceptibility, direct assessments using a standardized technique may help better define bruise susceptibility levels.

Many factors contribute to bruise susceptibility beyond impact method. The primary factors considered to alter bruise susceptibility are impact force (Schippers 1971; Thornton and Timm 1990), tuber pulp temperature at time of bruising (Thornton et al. 1973; Smittle et al. 1974; McGarry et al. 1996; Baritelle and Hyde 2001; Xie et al. 2020), and cultivar (Blahovec and Židová 2004; Kunkel et al. 1978; Horvath 1986). Additional factors contributing to greater bruise susceptibility include pre-harvest field conditions such as over mature tubers at vine kill (Corsini et al. 1999), delayed vine killing dates (Pavek et al. 1985), and wet soil conditions at harvest (Thornton and Timm 1990). Other factors include tuber biochemical characteristics like concentration of tyrosine, threonine, valine, serine, and glutamine (Steinfath et al. 2010), calcium, magnesium, nitrogen and/or potassium concentration in the tuber (Naumann et al. 2020; Kunkel et al. 1978; Karlsson et al. 2006), turgor levels (Kunkel and Gardner 1965; Konstankiewicz and Zdunek 2001; Lin and Pitt 1986), small cell size (Gancarz 2016), weak cellular structure (Konstankiewicz and Zdunek 2001), larger tuber mass (Baritelle and Hyde 1999), and higher specific gravities (Corsini et al. 1999; Baritelle and Hyde 2003). Differences in bruise susceptibility can be found between the two ends of the tuber (bud and stem) as well (Bajema et al. 1998; Reeve et al. 1969). These previous studies are a sample among a plethora of research trying to explain tuber blackspot and shatter bruise susceptibility. The distinction between blackspot and shatter bruise susceptibility is not always distinguishable in the literature, so some of the research conclusions include information pertaining to one or both types of bruises.

It is well-known that potato cultivars vary in bruise susceptibility. Biochemical components are one aspect that contributes to the variance in susceptibility between cultivars. One biochemical component found to be related to the formation of melanin (a component of blackspot bruise) is the isozymes of PPO (Bachem et al. 1994; Sabba and Dean 1994; Corsini et al. 1992). Hsu et al. (1988) detected PPO differences in three cultivars. Tuber tyrosine concentrations have also been linked to bruise susceptibility. Sabba and Dean (1994) found protein-bound tyrosine concentrations were higher and activity of proteinases were lower in bruise resistant cultivars, whereas free tyrosine was highly correlated to the development of melanin-like pigments. Strehmel et al. (2010) found there were higher levels of succinate and fumarate and lower levels of aconitate in a blackspot bruise susceptible cultivar. These biochemical components are related to the intracellular response due to mechanical stress or damage. Variation in biochemical components can also be seen within an individual tuber. The stem end of the tuber is more susceptible to blackspot bruise than the bud end (McGarry et al. 1996), whereas the bud end is more susceptible to shatter bruise (Hyde et al. 1992). Corsini et al. (1992) found free-tyrosine levels were different between cultivars and tuber ends and higher levels of free-tyrosine were correlated to blackspot bruise susceptibility. Tyrosine was reported to be 20 to 40% more concentrated in the stem end of the tuber compared to bud end (Reeve et al. 1969). Biochemical components involved in bruise development can vary between cultivars and between tuber ends, and the components are altered within the first 24 hours after impact (Partington et al. 1999). These variations suggest contributing factors of bruise susceptibility is not only from impact force, tuber pulp temperature at time of bruising, cultivar, pre-harvest conditions, or tuber characteristics, but biochemical components within a tuber determine bruise susceptibility as well.

One way to minimize damage throughout the entire post-harvest chain is to reduce drop heights as tubers transition from one surface to another during the harvest and handling process. Lowering drop heights in a handling operation has been well-documented to lower bruise potential or severity (Corsini et al. 1999; Mathew and Hyde 1997; Partington et al. 1999; Thornton and Bohl 1995; Xie et al. 2020). McGarry et al. (1996) indicated higher impact heights will result in shatter bruise, while lower impacts tend to cause blackspot bruise formation. Noble (1985) found long impact durations and low loading velocities produce blackspot bruise, whereas short impact durations and high loading velocities produce more shatter bruise. Impact duration and loading velocities help explain how the potato responds to different impact forces. The more a potato absorbs the force from a fall (long impact duration and low loading velocities) the greater the chance blackspot bruise develops. The less absorption from a higher fall, the greater the potential for shatter bruise to develop (short duration and high loading velocity). Mass of an object, drop height, and surface the object is dropped on are the major components involved in determining peak acceleration at time of impact and the velocity change experienced (Deng et al. 2020; Thomson and Lopresti 2018). Drop height and surface type potatoes are dropped on can be modified in a handling operation to lower the impact force. Decreasing drop heights as tubers transition from one surface to another can minimize damage throughout post-harvest equipment and cushioning surfaces potatoes are dropped on allow for greater drop heights before physical damage occurs. Using the two methods in unison can further reduce the potential for impact damage. Rady and Soliman (2015) found drop heights exceeding 15 cm onto steel surfaces caused damage, but after rubber coating the steel surface, drop heights could be increased to 25 cm before causing damage. In addition, tubers could be dropped up to 90 cm onto a layer of other tubers before damage occurred. The surface type potatoes are dropped on and drop height together can help determine bruise potential of potato tubers.

The overall goal of this research was to determine factors that contribute to bruise development and loss of potato quality at the main handling points within the post-harvest supply chain. To accomplish this, there were four major objectives conducted in this project. The first objective was to determine how storage duration contributes to bruise development and susceptibility. The second objective was to determine the progression of bruise development within 24 hours and if fresh bruises (up to five hours after impact) can be utilized as a rapid bruise detection indicator. The third objective was to examine bruise susceptibility of six cultivars at three different impact heights. The final objective was to examine the bruise potential in palletizing packaged potatoes at a fresh pack facility. These objectives aim to improve understanding of factors contributing to bruise development and susceptibility. That information can then be used to update bruise management programs in all areas of the post-harvest chain.

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Figures

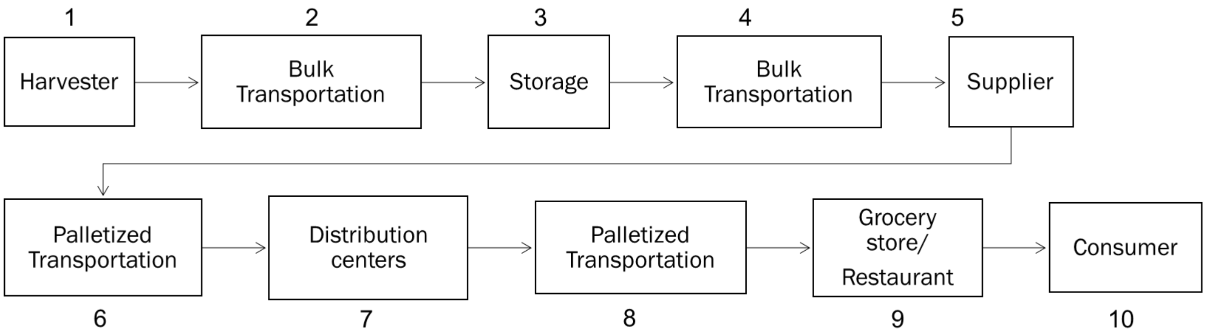

Figure 1-1. Schematic of the potato post-harvest handling operation chain. Each time potatoes are moved there is potential for impact injury and bruise. Depending on operation, steps three and four may not be involved.

Chapter 2: Risk Associated with Blackspot and Shatter Bruise Development and Susceptibility Throughout Storage

Abstract

Shatter and blackspot bruises sustained at harvest can affect the storability of potatoes. Understanding potato susceptibility to physical impact and bruise development in storage can help mitigate quality degradation. Three trials in 2019-20 and 2020-21 storage seasons were carried out to determine if bruises sustained at harvest change in storage; if time in storage alters tuber susceptibility to bruising; and if location on a tuber's surface area impacts bruise susceptibility. All trials included cultivars Russet Burbank and Russet Norkotah 278. In each trial, tubers were bruised using a 100 g impact device (18 cm drop height) and subsequently stored at 7.2°C (95% RH) at the University of Idaho Kimberly Research and Extension Center. In trial one, tubers were bruised at 12.7°C pulp temperature on the bud end and stem end at harvest and a subsample taken monthly from September to May (9 months) to assess bruise incidence and severity. In trial two, a sub-sample of tubers were bruised at 7.2°C pulp temperature at harvest, subsequent sub-samples bruised each month (8 months) and evaluated after 24 hours. In trial three, tubers were bruised at 12.7°C pulp temperature on 20 different locations on the surface of the tuber after one, four, and seven months in storage. All tubers were assessed for blackspot bruise incidence, severity, depth of bruise discoloration, and shatter bruise incidence. When tubers were bruised at harvest (trial one), the risk associated with blackspot bruise incidence, severity, and depth increased within the first month, but after the first month, blackspot bruises remained at similar levels for the rest of the storage period. Impact at harvest resulting in shatter bruise (trial one) did not develop further in storage. When removing tubers from storage (trial two), blackspot bruise susceptibility increased slightly, and shatter bruise susceptibility decreased throughout storage. Risk of shatter bruise was highest near the bud end of the tuber on both cultivars, whereas the risk of blackspot bruise increased with proximity to the stem end (trial three). The shoulder of the russet cultivars had increased blackspot bruise susceptibility compared to the flat surface indicating curvature of the tuber has a role in bruise susceptibility (trial three). For all trials, Russet Norkotah had lower overall blackspot and shatter bruise susceptibility than Russet Burbank. This study found the risk associated with blackspot and shatter bruise had minimal fluctuations when tubers are bruised at harvest and then placed into storage or when tubers are being unloaded from storage.

Introduction

Potatoes are handled during harvest, into and out of storage, throughout packing sheds or processing facilities, during transportation between locations, and from distribution centers to the consumer. Each time potatoes are handled, the potential for bruise is heightened. Two major types of bruises are blackspot and shatter bruise. Blackspot bruising occurs when a tuber's cell membranes are damaged, but the skin is unbroken. The intracellular membranes rupture causing a biochemical reaction to occur between polyphenol oxidase (PPO), tyrosine, and other substrates, resulting in melanin formation that appears as a dark discoloration at the area of impact (Edgell et al. 1998; Vreugdenhil et al. 2007; Dean 1996). Shatter bruises split the cell walls of the damaged area and expand outward and deep into the tissue, resulting in large cuts and visible splitting of the skin (Vreugdenhil et al. 2007; Hollingshead et al. 2020), as well as creating storability issues (McGarry et al. 1996) and entry points for pathogen infections (Singh et al. 2021).

In the Pacific Northwest, potatoes are an annual crop and only harvested once per year but are consumed year-round. The crop is stored after harvest for many months until the supply is needed for the consumer. Growers have raised the question if bruises sustained at harvest can develop into more severe bruises, stay the same, or lower in severity while in storage. Previous research has reported conflicting information about bruise development in storage. Skrobacki et al. (1989) found that, depending on impact force, the severity of the blackspot bruise at harvest could either increase or decrease 6 months into storage. Shatter bruise incidence was found to decrease with time in storage (Skrobacki et al. 1989). Ophuis et al. (1958) determined as potatoes sprouted in storage, the risk of blackspot bruise discoloration increased. There is a gap in research on bruise development in storage. In general, previous research did not examine bruises sustained at harvest that had time to develop for multiple months, but rather examined bruises that were less than a few days old at different times in storage. Examining bruise development throughout storage can help to answer questions of how tubers respond to damaging impacts with time in storage.

The risk of mechanical injury does not end once tubers are placed into storage, so understanding the susceptibly at the time of removal is important. Thornton and Davidson (1987) concluded that as potatoes were handled throughout a fresh pack operation there was a 15% increase in bruise from storage and transporting via truck to when potatoes initially entered the fresh pack facility. An additional 20% increase in bruise was measured once potatoes reached the packaging stage. That study demonstrated the risk of mechanical injury after removal from storage and the benefit to understanding the susceptibly of potatoes removed at various times.

Several previous research studies have evaluated the susceptibility of stored potatoes to subsequent impact damage upon removal from storage. Laerke et al. (2002) impacted potato tubers every two months in storage and evaluated for bruise 17 hours after impact each time. Depending upon cultivar, both blackspot and shatter bruise severity decreased from harvest to 6 months in storage (Laerke et al. 2002). Dean et al. (1993) impacted tubers at four different times during storage (one to eight months) and found blackspot bruise susceptibility decreased in storage. Edgell et al. (1998) used an impact device and found the formation of a blackspot bruise was more likely after six months compared to three months in storage. Tuber characteristics, including dehydration, age, and biochemical constituents, can change during storage, which potentially could alter bruise susceptibility (Shetty et al. 1998; Sawyer and Collin 1959; Praeger et al. 2009). This study sought to provide additional information about when the highest risk of blackspot and shatter bruise occurs for two common russet potato cultivars from harvest up to eight months in storage and provide bruise management strategies for removing potatoes from storage.

Previous research concluded the apical (bud) and stolon (stem) ends of tubers have differing bruise susceptibility levels (McGarry et al. 1996; Reeve et al. 1969). When tubers encounter mechanical damage, the cells directly beneath the periderm and the periderm itself are directly impacted. Tuber cell structure may play a large role in bruise susceptibility because cell response to a damaging impact can result in either blackspot (intracellular membrane degradation; Edgell et al. 1998) or shatter bruise (cell walls breaking; Konstankiewicz and Zdunek 2001). Cell size (Gancarz 2016), cell shape (Konstankiewicz et al. 2002), and location of cells on the tuber (Reeve et al. 1973) can determine how the intercellular structure is configured and in turn affect tissue susceptibility to blackspot and shatter bruises. Konstankiewicz et al. (2002) found cell size was variable in different cultivars, but cell shape was relatively constant; however, they only examined medium-sized tubers and sampled from the middle part of the tuber. More research needs to be conducted on how tubers respond to external forces on the entirety of the tuber's surface area. Different areas of the tuber may have different cellular structure, varying cellular strength, and bruise susceptibility. This study focused on bruise susceptibility as influenced by location on a tuber's surface area.

The goal of this study was to understand how time in storage contributes to blackspot and shatter bruise development and susceptibility. The distinction between bruise development and susceptibility is as follows: bruise development includes tubers that were impacted at harvest and evaluated each month in storage. Bruise susceptibility took a sample of tubers each month from storage and impacted the tubers to see if changes in resistance to bruise can be detected throughout storage. The first trial examined bruise development on the bud and stem end of tubers at harvest and throughout eight months of storage. The second trial examined bruise susceptibility throughout each month in an eight-month storage period that focused on each tuber end. A third trial examined bruise susceptibility on all surfaces of the tuber at three times in storage. Russet Burbank (R. Burbank) and Russet Norkotah (R. Norkotah) were used in all three trials. These two cultivars were chosen because they have been reported to differ in blackspot and shatter bruise susceptibility. Russet Burbank, which is used in the fresh and processing markets, has been extensively researched as a comparison cultivar for development of newer cultivars and is considered intermediately (Corsini 1996) or moderately (Love et al. 1994) susceptible to blackspot bruising. Russet Burbank susceptibility to shatter bruise is relatively high (Spear et al. 2017). Russet Norkotah, a major cultivar used in the fresh market, is relatively resistant to blackspot and shatter bruise (Spear et al. 2017).

Methods and Materials

There were three trials included in this study to determine (1) if bruises sustained at harvest change in storage (2) if storage duration alters tuber susceptibility to bruising and (3) if impact location on a tuber alters bruise susceptibility in the 2019-20 and 2020-21 storage seasons at the University of Idaho Kimberly Research and Extension Center (KREC). Certified R. Burbank and R. Norkotah 278 seed potatoes were planted at KREC on April 25 for the 2019 crop year and April 21 for the 2020 crop year. The crops were grown under University of Idaho recommendations for fertility, irrigation, and pest control. Each year, plants were flail-mowed 141 days after planting (DAP) and harvested 154 DAP. Tubers received a thermal application of the sprout inhibitor isopropyl (3-chlorophenyl) carbamate (chlorpropham; Aceto Agricultural Chemicals Corporation) at 22 ppm on November 26th, 2019 and November 19th, 2020. Post-harvest trial procedures are discussed in the following sections.

Bruise impact device protocols

Washed potatoes (170 to 300 g) were marked on a predetermined location void of obvious defects for subsequent impact and bruise evaluations. The marked spots allowed for ease of knowing the location of the impact and to facilitate evaluations. In all trials, tubers were bruised using an impact device that dropped a 100 g steel weight from an 18 cm height to a deliver uniform impact on a stationary tuber. For trials one and two, tubers were impacted on two locations on the bud end and two locations on the stem end of each tuber in 2019. Preliminary data showed no significant differences between the two impacts sites on each end of the tuber, therefore in 2020 only one spot was impacted on each end. In trial three, 20 spots were impacted on each tuber: the spots were divided into four longitudinal lines (two flat surfaces and two shoulders) and were marked in five locations (bud, mid-bud, middle, mid-stem, stem) per longitudinal line from the bud end to the stem end of the tuber. Figure 2-1 depicts how tubers were marked for impact in trial three.

Bruise development throughout storage: Trial one

At harvest, tubers were placed at 12.8°C and 95% relative humidity (RH) to equilibrate to a constant pulp temperature. The following day, all tubers (675 tubers per cultivar) were impacted as described above. A 15-tuber sample per replicate (five replicates per cultivar) was randomly sampled for the at-harvest evaluation; the sub-sample was held at 7.2°C and 95% RH for 24 hours and then evaluated for bruise as described below. In 2020, an additional evaluation was completed 48 hours after the tubers were impacted to ensure direct moving to the storage temperature did not affect the development of bruise. We found no statistical differences between the 24- and 48-hour evaluations, therefore the analysis concentrated on the 24-hour data only (data not shown). The remaining impacted tubers were cured at 12.8°C for two weeks, ramped down at a rate of 0.3°C/day until temperature reached 7.2°C and stored at 7.2°C (95% RH) for the remainder of the study. Each consecutive month until May (8 months in storage), a sub-sample was removed from storage and evaluated for bruise. There was an average of 30 days between evaluations.

Monthly tuber bruise susceptibility: Trial two

At harvest, a 15-tuber sub-sample per replicate (five replicates per cultivar) was placed directly into 7.2°C storage to equilibrate to 7.2°C pulp temperature. After equilibration, the at-harvest sub-sample was impacted as described above, held at room temperature (21.1°C) for 24 hours and then evaluated for bruise. The remaining harvested tubers were placed at 12.8°C (95%RH) for two weeks, ramped down at a rate of 0.3°C/day until temperature reached 7.2°C, and stored at that temperature with 95% RH for 8 months. Each subsequent month, a 15-tuber sample replicate (five replicates per cultivar) was removed from storage, impacted, held at room temperature (21.1°C), and evaluated 24 hours later. There was an average of 30 days between evaluations.

Response of tuber location to impact: Trial three

Trial three was completed during the 2019-20 storage season and focused on bruise susceptibility of varying locations on a tuber. Tubers were placed directly into storage at 12.8°C for two weeks after harvest, ramped down at a rate of 0.3°C/day until temperature reached 7.2°C (95%RH), and stored at that temperature for 7 months. A 20-tuber sample per replicate (four replicates per cultivar) was removed from storage one, four, and seven months after harvest. Once removed from storage, tubers were warmed to pulp temperatures of 12.8°C, impacted as described above, stored at room temperature (21.1°C) and evaluated for bruise 24 hours later as described below.

Evaluation of bruise

The marked impacted areas were peeled using a standard vegetable peeler (Kuhn Rikon Original Swiss Peeler, Switzerland) and evaluated for blackspot bruise severity, bruise depth, incidence of blackspot bruise, and incidence of shatter bruise. Blackspot bruise severity was rated on the darkest color observed on a scale from 1 to 4: 1= no color, slight cell deformation, 2=light gray color, not severe but discoloration occurred, 3=dark gray color, severity is moderate, dark but not extreme, 4=dark gray/black color, severity is extreme (Figure 2-2). Blackspot bruise depth was evaluated by recording the number of slices removed by the peeler until no bruise was present. Preliminary data determined the average thickness of each slice to be 1.27 mm. Blackspot bruise depth was calculated as the number of peels * 1.27 mm. Presence of shatter bruise was determined if there was a fracture in the cell wall visible after the first layer (1.27 mm) of the periderm was removed. Trial three excluded depth from the evaluation. Incidence of blackspot and shatter bruise were calculated by the presence or absence of bruise and calculated as a percentage of the impacted areas showing a bruise.

Statistical Analysis

Blackspot bruise severity, bruise depth, blackspot bruise incidence and shatter bruise incidence were analyzed using the analysis of variance (ANOVA) procedures in R (RStudio, package car version 3.0-9, 2020; Fox and Weisberg 2019). For trial one and two, a mixed-effects model was fitted where month in storage, tuber end, cultivar, month in storage by tuber end, month in storage by cultivar, tuber end by cultivar, and month in storage by tuber end by cultivar were considered fixed effects and the replicate nested into each month was considered a random effect. For trial three, a linear model was fitted where time in storage, location via tuber side, location via longitudinal placement, time in storage by location via tuber side, time in storage by location via longitudinal placement, location via tuber side by location via longitudinal placement, and time in storage by location via tuber side by location via longitudinal placement were considered fixed effects. Significant differences among means for all response variables were compared at alpha of 0.05 by estimated marginal means procedures (RStudio, package emmeans version 1.6.1, 2020; Lenth 2021).

Results

Bruise development throughout storage: Trial one

There was a significant increase from harvest to one month in storage for blackspot bruise incidence (58 to 66%), severity (1.9 to 2.0 rating), and depth (2.9 to 3.6 mm) (P<0.0001; Table 2-1). From one month until the eighth month in storage similar levels of blackspot bruise incidence (66 to 72%), severity (2.0 to 2.2 rating), and depth (3.6 to 4.2 mm) were observed (Table 2-1). Shatter bruise incidence was similar at harvest (6%) and eight months into storage (7%), although there was variability between one month and seven months into storage (9 to 12%; P=0.02; Table 2-1). The variability in shatter bruise incidence was assumed to be due to sample variability since shatter bruise incidence was so low throughout the trial (6-12%). The bud end had lower blackspot bruise incidence (50%), severity (1.7 rating), and depth (2.4 mm) than the stem end (87%, 2.5 rating, 5.0 mm, respectively); however, the bud end had higher shatter bruise incidence (15%) than the stem end (4%). R. Norkotah was lower than R. Burbank in all blackspot and shatter bruise variables examined (Table 2-1).

There was a significant interaction between tuber end and month in storage for blackspot bruise incidence (P< 0.0001) and blackspot bruise depth (P=0.003). There was no statistical difference in monthly blackspot bruise incidence on the stem end of the tuber (84 to 90%), whereas the bud end incidence was significantly lower (31%) at harvest and gradually increased with time in storage (45 to 61%; Figure 2-3a). Blackspot bruise depth on the stem end showed variability throughout storage but had similar depth at harvest (4.4 mm) and eight months of storage (4.6 mm). Blackspot bruise depth on the bud end at harvest (1.4 mm) increased from one month to eight months in storage (2.2 to 2.9 mm; Figure 2-3b). There was a significant effect between tuber ends and cultivar for blackspot bruise severity (*P*= 0.001). The bud end had lower blackspot bruise severity for each cultivar. Russet Burbank had higher severity for both ends compared to R. Norkotah (Figure 2-4). There was a significant effect between tuber ends and cultivar for shatter bruise incidence (*P*<0.0001; Figure 2-5). The bud end had higher shatter bruise incidence for both cultivars, but there was a larger difference in incidence between tuber ends for R. Burbank (difference of 12%) compared to R. Norkotah (difference of 5%).

Monthly tuber bruise susceptibility: Trial two

Month in storage, tuber end and cultivar were significant for all blackspot bruise and shatter bruise variables (Table 2-2; *P*<0.0001). Blackspot bruise incidence was 79% at harvest and significantly increased to 85% by eight months in storage (Table 2-2). During late storage (six and seven months in storage) there was a significant decrease in blackspot bruise incidence (71 to 72%) compared to incidence at harvest (79%). Blackspot bruise severity had a 2.3 rating at harvest and significantly increased to a 2.7 rating by eight months in storage (Table 2-2). Blackspot bruise depth significantly increased from 3.9 mm at harvest to 5.8 mm at eight months in storage. Shatter bruise incidence significantly decreased from harvest (11%) to the second month in storage (8%). Shatter bruise remained consistent from the second month in storage (7 to 8%) until the seventh month in storage when shatter bruise incidence significantly decreased to 2%. Overall, the bud end had lower blackspot bruise incidence (62%), severity (1.8 rating), and depth (3.3 mm) than the stem end (91%, 2.8 rating, 5.5 mm, respectively); however, the bud end had higher shatter bruise incidence (11%) than the stem end (3%). R. Norkotah was lower in all blackspot and shatter bruise variables examined than R. Burbank (Table 2-2).

There was a significant interaction between tuber end and month in storage for all variables examined (Figure 2-6). The stem end increased in blackspot bruise incidence from harvest to eight months in storage, whereas the bud end had similar incidence at harvest compared to eight months in storage (Figure 2-6a). The bud end had a decrease in incidence during the sixth and seventh month in storage that was not observed in the stem end. Blackspot bruise severity on the stem end increased from a 2.6 rating at harvest to 3.2 rating by eight months in storage whereas the bud end was similar at harvest (1.9 rating) and eight months in storage (2.1 rating; Figure 2-6b). Blackspot bruise depth decreased on the bud end from harvest to seven months (3.2 to 2.6 mm) in storage, then increased the eighth month in storage (4.5 mm), whereas the stem end gradually increased from harvest to eight months in storage (4.6 to 7.2 mm; Figure 2-6c). The stem end had similar shatter bruise incidence throughout storage (0 to 5%), whereas the bud end gradually decreased (17 to 5%) throughout the months in storage.

There was a significant interaction between cultivar and months in storage for all variables examined (Figure 2-7). For blackspot bruise incidence, severity, and depth, R. Norkotah was lower at harvest (66%, 1.9 rating, 3.1 mm, respectively) than R. Burbank at harvest (91%, 2.6 rating, 4.7 mm). For blackspot bruise incidence in the remaining months of storage, R. Norkotah and R. Burbank responded similarly (Figure 2-7a). Blackspot bruise severity for R. Norkotah remained lower than R. Burbank until the fifth month in storage then was similar to R. Burbank for the remainder of storage (Figure 2-7b). Blackspot bruise depth for R. Norkotah remained lower than R. Burbank until the fourth month in storage, then was similar to R. Burbank for the remainder of storage (Figure 2-7c). Russet Norkotah had less variability between months in storage for shatter bruise incidence (0 to 5%) than R. Burbank, which showed a significant decrease in shatter bruise with time in storage (17 to 4%; Figure 2-7d).

The bud end was lower in blackspot bruise incidence, severity, and depth than the stem end for both cultivars, although there was a higher variance between tuber ends for R. Burbank than tuber ends for R. Norkotah for all blackspot bruise variables (Figure 2-8). There was no difference in shatter bruise incidence between tuber ends for R. Norkotah (3 to 4%), whereas the bud end for R. Burbank (18%) was higher than the stem end (4%; Figure 2-8d). There was a significant interaction among cultivar, tuber end, and month in storage for blackspot bruise severity and shatter bruise incidence (Figure 2-9). R. Norkotah had more variability in severity on the stem end from harvest to eight months in storage (2.1 to 3.3 rating) than R. Burbank on the stem end (3.0 to 3.2 rating; Figure 2-9a). The bud end of R. Norkotah had lower severity (1.7 rating) than the bud end of R. Burbank (2.2 rating) at harvest, then both bud ends responded similarly in severity at each additional month in storage. The bud end of R. Burbank decreased in shatter bruise incidence throughout storage (25 to 7%) whereas R. Norkotah’s bud end and both cultivar’s stem ends remained relatively low throughout all of storage (0 to 9%; Figure 2-9).

Response to impact on different locations of tuber: Trial three

This trial determined how time in storage and location of impact between tuber sides (shoulder and flat) and longitudinal placement (bud, mid-bud, middle, mid-stem, stem) affected blackspot bruise incidence, severity and shatter bruise incidence. Russet Burbank and R. Norkotah were analyzed separately. Location of impact via longitudinal placement and month in storage affected all response variables examined for both R. Burbank and R. Norkotah (*P*<0.001). Location of impact on the tuber side affected blackspot bruise incidence and severity (*P*<0.001) but did not affect shatter bruise incidence for either cultivar (R. Burbank, *P*=0.58; R. Norkotah, *P*=0.53).

Russet Burbank

Blackspot bruise incidence and severity showed an increasing gradient in the longitudinal line from the bud to the stem end of the tuber. From the bud to the stem end, blackspot incidence and severity incrementally increased on impacted spots until it reached the mid stem (24 to 80%; 1.3 to 2.2 rating; Table 2-3). Conversely, shatter bruise incidence was higher on the bud end (13%) and decreased as it approached the stem end (1%). The shoulder of the tuber had significantly higher blackspot bruise incidence (67%) and severity (2.0 rating) compared to the flat surface of the tuber (27%, 1.3 rating, respectively; Table 2-3). There was no significant difference in shatter bruise incidence between the shoulder and flat surface of the tuber (6%; Table 2-3). Time in storage significantly increased blackspot bruise incidence (42 to 51%) and severity rating (1.5 to 1.8; Table 2-3). Shatter bruise incidence incrementally decreased in storage (9 to 3%; Table 2-3).

There was a significant interaction between longitudinal placement of impact and tuber side for blackspot bruise incidence and severity (*P*<0.001). Blackspot bruise incidence and severity incrementally increased on the shoulder of the tuber as it approached the stem end; however, incidence and severity did not increase on the flat surface until the impact location reached the stem end (Figure 2-10). Interestingly, shatter bruise incidence did not follow this pattern and decreased at the same level as it longitudinally approached the stem end location (*P*= 0.89; Figure 2-11).

There was a significant interaction between month in storage and longitudinal placement of impact location for blackspot bruise incidence (*P*=0.01), severity (*P*=0.01), and shatter bruise incidence (*P*=0.003). Blackspot bruise incidence and severity increased from the first month in storage to the seventh month in storage for the mid-bud, middle, and mid-stem locations, whereas the bud and stem end locations remained similar in incidence and severity (Figure 2-12). Shatter bruise incidence decreased from the first month of storage to the seventh month of storage for the bud, mid-bud, and middle locations, whereas the mid-stem and stem locations remained similar throughout storage (Figure 2-13).

There was a significant interaction between month in storage and tuber side for blackspot bruise incidence and blackspot bruise severity (*P*< 0.001). The flat surface of the tuber had similar incidence (26 to 27%) throughout storage, but the shoulder side of the tuber increased each month examined (56 to 76%; Figure 2-14a). Blackspot bruise severity on the flat surface remained constant (1.3 rating) throughout storage, and the shoulder increased each month examined (1.8 to 2.2 rating; Figure 2-14b). There was no interaction between month in storage and tuber side on shatter bruise incidence (*P*= 0.79; Figure 2-15). There was a significant (*P*<0.001) interaction between month in storage, longitudinal placement, and tuber side for blackspot bruise incidence, but followed similar trends throughout storage as described by the two-way interactions.

Russet Norkotah

The bud and mid-bud of the tuber responded similarly in terms of blackspot bruise incidence (32 to 33%) and blackspot bruise severity (1.3 to 1.4; Table 2-4). From the mid-bud to the stem end, blackspot bruise incidence and severity increased (32 to 73%, 1.4 to 2.0 rating, respectively). The shoulder of the tuber had higher blackspot bruise incidence (67%) and severity (2.0 rating) compared to the flat surface of the tuber (27%, 1.3 rating, respectively; Table 2-4). The influence of time in storage on blackspot bruise incidence and severity was significant (*P* <0.001). Blackspot bruise incidence increased from 44% to 52% and the severity rating increased from 1.5 to 1.8 between early and late storage (Table 2-4). Shatter bruise only occurred on the bud end of the tuber for Russet Norkotah (3%; Table 2-4).

There was a significant interaction between longitudinal placement and tuber side for blackspot bruise incidence and severity (*P*<0.001, Figure 2-16). Blackspot bruise incidence and severity increased on the shoulder of the tuber as it approached the stem end; however, the flat surface of the tuber did not increase until the impact was at the closest impacted area to the stem end (Figure 2-16). There was a significant interaction for blackspot bruise severity between time in storage and longitudinal placement (*P*=0.01). Blackspot bruise severity increased from the first month in storage to the seventh month in storage for the middle, mid-stem, and stem locations, whereas the bud and mid-bud locations remained similar throughout storage (Figure 2-17).

There was a significant interaction for month in storage and tuber side for blackspot bruise incidence (*P*=0.04) and severity (*P*=0.03). Blackspot bruise incidence and severity increased slightly on the flat surface of the tuber throughout storage. On the shoulder of the tuber blackspot bruise incidence was similar throughout storage (66 to 68%), whereas severity incrementally increased each month (1.8 to 2.1 rating; Figure 2-18).

Discussion

This study examined the potential for bruises sustained at harvest to continue to develop once tubers were placed into storage. When tubers are bruised at harvest, blackspot bruise incidence, severity, and depth increased within the first month, but after the first month, blackspot bruises remained at similar levels for the remainder of time in storage. This increase in bruise development within the first month may be explained by the response observed on the bud end of the tuber. When bruises were sustained at harvest on the stem end, they did not change in incidence, severity, or depth throughout storage. The bud end, however, had a significant increase for blackspot bruise incidence and depth within the first month of storage. The response observed between ends of the tuber and bruise incidence and depth could be due to differences in age of cells between tuber ends at harvest (Xu et al. 1998).

The continued development of blackspot bruise following harvest was not dependent on cultivar. Russet Burbank incurred more blackspot and shatter bruise incidence, higher blackspot bruise severity, and deeper blackspot bruises than R. Norkotah when impacted at harvest suggesting R. Norkotah had a lower risk of sustaining blackspot and shatter bruises compared to R. Burbank at harvest. However, these bruises developed at the same rate throughout storage for each cultivar.

Blackspot bruises observed at harvest may have been lower in incidence, severity and depth compared to the first month in storage due to processes that occur during the curing period. The industry standard of curing includes holding tubers at warmer temperatures (10 to 12.8 °C) with high relative humidity (95 to 98%) for two to three weeks at the beginning of the storage season (Wang et al. 2020). The curing procedures used in this study included holding tubers at 12.8°C for two weeks, then ramped down the temperature at a rate of 0.3°C/day until temperature reached 7.2°C. For the at-harvest evaluation, this sub-sample did not have a curing period before evaluations were made and was placed directly at the storage temperature (7.2 °C) after impact. Curing is done to help wound healing of potatoes and limit weight loss (Pinhero et al. 2009; Wang et al. 2020; Kleinkopf and Olsen 2003). The wound healing process, also known as suberization, is a tuber's way of defending itself against cellular damage incurred from physical damage (Singh et al. 2021; Lulai 2007). Initial layers of defense develop two to three days after impact (Lulai 2007), but the final steps in the process, development of phellem cells, were not observed to complete until 28 days after wounding. Although most of the development of phellem cells was complete 5 to 14 days after damage (Singh et al. 2021). The phellem cells, which consists of phellogen layer, is one of the main components of the suberized periderm which can surround a blackspot bruise area as a way of inhibiting further tissue damage (Reeve 1968). The lower risk of blackspot bruise incidence, severity, and depth observed at harvest could be because bruise development continued until wound healing was complete. The highest weight loss occurs in the first 8 weeks of storage, depending on storage temperature (Iritani et al. 1977). This additional weight loss during this time may have altered the incidence, severity, and depth of blackspot bruises as well. Future research needs to exclude curing from the experiment to explore if this lower risk at harvest, albeit 8% lower, was due to time in storage or a factor of the curing process.

Impacts at harvest resulting in shatter bruise did not develop further in storage. Sub-sampling to know how much shatter bruise occurred on a commercial operation could be done at harvest. This study did not measure severity of shatter bruise, and although incidence did not increase, severity may have changed. Shatter bruise impairs the suberization ability of potato tissue because of the irregular fracture of the wound leaving the tuber vulnerable to other infections (Lulai 2007). However, overall incidence of shatter bruise was low in this study due to the method of impact used. Future research should examine shatter bruise severity.

This study also examined the risk associated with handling tubers as they are unloaded from storage. Blackspot bruise incidence, severity, and depth increased from harvest to the eighth month in storage. This increase was primarily observed on the stem end of the potato. The bud end had minor fluctuations in blackspot bruise incidence, severity, and depth during each month of storage, but by the eighth month susceptibility was similar to tubers impacted at harvest. Even though tuber ends responded differently to impact at different times in storage, overall blackspot bruise susceptibility was constant throughout storage. To illustrate this consistency, a severity scale was modified from Sawyer and Collin (1960) to examine the average blackspot bruise incidence and severity rating each month tubers were impacted in storage (Table 2-5). This scale emphasized that blackspot bruise susceptibility remained in a moderate category throughout the entirety of the storage months examined. The risk associated with handling tubers after unloading from storage was consistent regardless of the time in storage they were removed. Overall, risk of blackspot was higher in R. Burbank than R. Norkotah, especially at harvest. When unloading from storage, both cultivars would have similar blackspot bruise incidence, but R. Norkotah could have lower blackspot bruise severity and depth until late storage where it would respond similar to R. Burbank. If potatoes have a high level of blackspot bruise at harvest, extra care may be needed with subsequent handling out of storage because the risk associated with blackspot bruises would still be high during this time. By eight months in storage, there appears to be an upward shift in the tuber's susceptibility to blackspot bruise. This could be attributed to higher tuber weight loss, age, or even though the potatoes were sprout inhibited, initiation of sprouting can occur after long-term storage.

The longer the duration in storage, the less chance of subsequent shatter bruising to occur from unloading storages, which agreed with conclusions of Skrobacki et al. (1989). This decrease in shatter bruise incidence was primarily seen on the bud end of the tuber and with R. Burbank. Overall, a major decrease in shatter bruise incidence was seen by the seventh month in storage. This decrease may be due to physiological or biochemical changes in the tuber that occur in storage. Respiration, water loss, and sprout development all occur during storage (Pinhero et al. 2009). These physiological and biochemical changes lower tuber turgor (Edgell et al. 1998), which has been found to lower the risk of shatter bruise (Smittle et al. 1974). Higher turgor in cells creates more tension on the cell walls (Konstankiewicz and Zdunek 2001) making cells more susceptible to impacts that cause shatter bruises. So as tuber turgor decreases throughout storage, shatter bruise does as well. Shatter bruise was almost always accompanied by blackspot bruise throughout this study (data not shown) emphasizing that potatoes impacted during handling will most likely encounter both types of bruises, so understanding the risk for both bruises is beneficial.

Previous research examined biochemical components which may contribute to differences in bruise susceptibility within a tuber observed as in this study. Tyrosine is considered a primary substrate for the formation of melanin (Belknap et al. 1990), a critical component in the development of blackspot bruise. Tyrosine has been reported to be 20 to 40% more concentrated in the stem end of the tuber as compared to the bud end (Reeve et al. 1969). Various cultivars have been found to have different concentrations of tyrosine and other phenolic substrates of PPO, which are active components in blackspot bruise development (Stark et al. 1985). Stark et al. (1985) also emphasized that for bruise resistant cultivars, tyrosine was incorporated into proteins rather than being used in PPO activity. Rastovski and Es (1981) concluded that concentrations of chlorogenic acid, tyrosine, phenolase, peroxidase, catalase, ascorbic acid, acidity, and iron were higher in the stem end. The bud end was reported to have higher citric acid, phosphorus, potassium, and solanine-solanidine (Rastovski and Es 1981). Yet, ascorbic acid has also been reported to be almost double in concentration in the bud end compared to the stem end (Smith and Gillies 1940). Mondy and Leja (1986) concluded bruised tissue had lower ascorbic acid present than unbruised tissue and Lin et al. (2021) concluded ascorbic acid may inhibit PPO activity. There are some contradictions as to how certain biochemical components relate to bruise, as presented about ascorbic acid concentrations between the bud and the stem end. Although, differing biochemical components may suggest why there are differences in blackspot bruise susceptibility among the surface area of the tuber.

A major factor in determining bruise susceptibility is location of impact on the tuber. This study found blackspot bruise susceptibility incrementally changed from one end of the tuber to the other. One interesting observation found when tubers were impacted on 20 different locations was the unique response between the tuber sides. The flat surface had lower blackspot and shatter bruise incidence regardless of where the impact occurred. This conclusion emphasized that biochemical components between tuber ends cannot solely answer the variability seen in tuber bruise susceptibility. Cellular structure may play a larger role compared to biochemical components than previously thought. During plant growth, tuberization occurs at the stolon tip and includes rapid cell division and expansion (Xu et al. 1998). When tubers are forming in the stem region (where the newest tissue is forming), the cells first enlarge then divide longitudinally, whereas in the bud region the cells divide transversally and then elongate (Xu et al. 1998). The curvature between the shoulder and face of the tuber may have differing cellular growth as well. The way these cells divide during growth dictate how cell structure develops and may allude to why different areas of the tuber have different bruise susceptibility levels. Future research should examine cell size along the entirety of the tuber surface area to further understand the physical and cellular properties involved in bruise susceptibility of tubers.

Cellular structure in potato tissue is assumed to work as a unit because the cells are very closely connected in homogeneity (Gao and Pitt 1991). The shape of parenchyma cells is assumed to have 8 hexagonal faces and 6 square faces which allows for strong intercellular bonding (Gao and Pitt 1991). Since these cells can bond to each other on many different faces, cell orientation might also aid in strengthening the cell structure (Gao and Pitt 1991) alluding to the difference in bruise damage seen throughout the surface areas examined. Cellular structure and cell orientation in different areas of the tuber might explain the differences in bruise susceptibility observed. This study reinforced the concept that the shoulder and stem end of a tuber have higher blackspot bruise susceptibility whereas the bud end and face were more susceptible to shatter bruise. When potato samples are taken to examine bruise levels in commercial operations, if blackspot bruise is seen on the bud end or shatter on the stem end, bruise susceptibility and handling conditions are extreme, and modifications need to be made. The susceptibility of the various locations on the tuber also provides opportunities for future research to examine the biochemical, mechanical, and physical differences between the surface area of the tuber, especially relating to the face and shoulder of the tubers.

Conclusion

This study found that bruises sustained at harvest will remain consistent, although potentially slightly higher than observed at harvest, throughout most of storage. Sub-sampling early in storage could provide a strong idea of the bruise level that will be seen through the rest of the storage season. These results help answer the question about the risk of increased bruise development and severity from impacts sustained at harvest with time in storage. It also reinforces the importance of focusing on bruise mitigation programs at harvest and the need for additional research on tuber characteristics that increase tuber susceptibility at harvest. When removing tubers from storage, the results indicated blackspot bruise susceptibility increased slightly, and shatter bruise susceptibility decreased throughout storage. These fluctuations occurred primarily between early and late storage, whereas in between, the bulk of the storage season, susceptibility was consistent for both types of bruises. This study examined two russet cultivars used in the fresh pack industry and found R. Norkotah was lower in susceptibility to both bruise types at the 18 cm drop height compared to R. Burbank. Tuber ends responded differently to both types of bruises in all the trials throughout this study. Risk of shatter bruise was evident near the bud end of the tuber on both cultivars, whereas the risk of blackspot bruise increased with proximity to the stem end. The shoulder of russet cultivars had increased bruise susceptibility compared to the flat surface indicating curvature of the tuber has a role in bruise susceptibility. Future research needs to examine the physical, cellular, and biochemical components on all of the tuber's surface area to understand the responses seen when individual tubers were impacted. Future research should examine additional cultivars, impact temperatures, and storage temperatures to further resolve the role time in storage may have on bruise development and susceptibility.

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Tables

Table 2-1. Tubers impacted at harvest and evaluated for bruise development throughout storage: Main effect of month in storage, tuber end, and cultivar on blackspot bruise incidence, severity rating, depth, and shatter bruise incidence. Results are means of two years.

	Blackspot bruise Incidence (%)[1]	Blackspot bruise severity rating (1-4) [2]	Blackspot bruise depth (mm)	Shatter bruise incidence (%)
Month in storage				
Harvest	58 a	1.9 a	2.9 a	6 a
1	66 b	2.0 b	3.6 bc	12 c
2	68 bc	2.1 bcd	3.7 bcd	10 bc
3	69 bc	2.1 bc	3.5 b	11 c
4	69 bc	2.1 cd	3.7 bcd	11 c
5	71 c	2.1 bcd	4.0 de	10 abc
6	69 bc	2.1 bcd	3.9 cde	9 abc
7	71 c	2.2 d	4.2 e	11 c
8	72 c	2.1 bcd	3.8 bcd	7 ab
P-value	<0.0001	<0.0001	<0.0001	0.02
Tuber end				
Bud	50 a	1.7 a	2.4 a	15 b
Stem	87 b	2.5 b	5.0 b	4 a
P-value	<0.0001	<0.0001	<0.0001	<0.0001
Cultivar				
R. Burbank	74 b	2.2 b	4.1 b	14 b
R. Norkotah	63 a	1.9 a	3.3 a	5 a
P-value	<0.0001	<0.0001	<0.0001	<0.0001

[1] Values followed by the same letter are not significantly different ($\alpha<0.05$) for each variable within each column.

[2] Blackspot bruise severity 1 to 4: 1= no color, slight cell deformation, 2=light gray color, not severe but discoloration occurred, 3=dark grayish color, severity is moderate, dark but not extreme, 4=dark gray/black color, severity is extreme.

Table 2-2. Tubers impacted at harvest and impacted each month in storage: Main effect of month in storage, tuber end and cultivar on blackspot bruise incidence, severity rating, depth, and shatter bruise incidence. Results are means of two years.

	Blackspot bruise Incidence (%)[1]	Blackspot bruise severity rating (1-4) [2]	Blackspot bruise depth (mm)	Shatter bruise incidence (%)
Month in storage				
Harvest	79 cd	2.3 ab	3.9 ab	11 c
1	82 de	2.4 c	4.4 c	9 bc
2	76 abc	2.3 ab	4.2 bc	8 b
3	75 abc	2.2 a	3.8 a	8 b
4	77 bcd	2.3 bc	4.4 c	7 b
5	76 abc	2.3 abc	4.4 c	8 b
6	71 a	2.3 ab	4.6 c	7 b
7	72 ab	2.3 ab	4.0 ab	2 a
8	85 e	2.7 d	5.8 d	3 a
P-value	<0.0001	<0.0001	<0.0001	<0.0001
Tuber end				
Bud	62 a	1.8 a	3.3 a	11 a
Stem	91 b	2.8 b	5.5 b	3 a
P-value	<0.0001	<0.0001	<0.0001	<0.0001
Cultivar				
R. Burbank	79 b	2.4 b	4.7 b	11 b
R. Norkotah	75 a	2.2 a	4.1 a	3 a
P-value	0.01	<0.0001	<0.0001	<0.0001

[1] Values followed by the same letter are not significantly different (α<0.05) for each variable within each column.

[2] Blackspot bruise severity 1 to 4: 1= no color, slight cell deformation, 2=light gray color, not severe but discoloration occurred, 3=dark grayish color, severity is moderate, dark but not extreme, 4=dark gray/black color, severity is extreme.

Table 2-3. Russet Burbank response to impact on different tuber locations: Main effect of longitudinal placement (bud, mid-bud, middle, mid-stem, stem), tuber sides (flat, shoulder), and month in storage on blackspot bruise incidence and severity and shatter bruise incidence. Results are means of three experiments in one storage season.

	Blackspot bruise incidence (%)[1]	Blackspot bruise severity rating (1 to 4)[1,2]	Shatter bruise incidence (%)[1]
Longitudinal placement			
Bud	24 a	1.3 a	13 c
Mid Bud	33 b	1.4 b	8 b
Middle	44 c	1.6 c	8 b
Mid Stem	53 d	1.8 d	2 a
Stem	80 e	2.2 e	1 a
P-value	<0.001	<0.001	<0.001
Tuber side			
Flat surface	27 a	1.3 a	6 a
Shoulder	67 b	2.0 b	6 a
P-value	<0.001	<0.001	0.58
Month in storage			
1	42 a	1.5 a	9 c
4	48 b	1.7 b	6 b
7	51 b	1.8 b	3 a
P-value	<0.001	<0.001	<0.001

[1] Values followed by the same letter are not significantly different ($\alpha<0.05$) for each variable within each column.

[2] Blackspot bruise severity was rated on a scale from 1 to 4: 1= no color, slight cell deformation, 2=light gray color, not severe but discoloration occurred, 3=dark grayish color, severity is moderate, dark but not extreme, 4=dark gray/black color, severity is extreme.

Table 2-4. Russet Norkotah response to impact on different tuber locations: Main effect of longitudinal placement (bud, mid-bud, middle, mid-stem, stem), tuber sides (flat, shoulder), and month in storage on blackspot bruise incidence and severity and shatter bruise incidence. Results are means of three experiments in one storage season.

	Blackspot bruise incidence (%)[1]	Blackspot bruise severity rating (1 to 4)[1,2]	Shatter bruise incidence (%)[1]
Longitudinal placement			
Bud	33 a	1.3 a	3 b
Mid Bud	32 a	1.4 a	0 a
Middle	46 b	1.7 b	0 a
Mid Stem	53 c	1.8 c	0 a
Stem	73 d	2.0 d	1 a
P-value	<0.001	<0.001	<0.001
Tuber side			
Flat surface	27 a	1.3 a	1 a
Shoulder	67 b	2.0 b	1 a
P-value	<0.001	<0.001	0.53
Month in storage			
1	44 a	1.5 a	2 b
4	46 a	1.6 b	0 a
7	52 b	1.8 c	0 a
P-value	<0.001	<0.001	<0.001

[1] Values followed by the same letter are not significantly different ($\alpha<0.05$) for each variable within each column.

[2] Blackspot bruise severity was rated on a scale from 1 to 4: 1= no color, slight cell deformation, 2=light gray color, not severe but discoloration occurred, 3=dark gray color, severity is moderate, dark but not extreme, 4=dark gray/black color, severity is extreme.

Table 2-5. Blackspot bruise monthly tuber susceptibility scale and categorization as influenced by month in storage.

Month	Blackspot bruise susceptibility scale[1]	Category[2]
Harvest	45	Moderate
1	49	Moderate
2	44	Moderate
3	41	Moderate
4	44	Moderate
5	44	Moderate
6	41	Moderate
7	41	Moderate
8	57	Moderate

[1] Blackspot bruise susceptibility scale is modified from Sawyer and Collin (1960) bruise index scale that takes into consideration the average blackspot bruise incidence and average severity rating. The severity scale is on a 1 to 4 scale. The formula is (percentage of blackspot bruise*severity rating)/4. Bruise susceptibility scale is from 0 to 100 with 0 being the least susceptible and 100 being the most susceptible.

[2] Categories were determined by low, moderate, or high blackspot bruise severity with 0 to 33 being low, 34 to 66 being moderate, and 67 to 100 being high.

Figures

Figure 2-1. Predetermined impact locations on each tuber for trial three. Twenty locations were impacted on each tuber: each of the four sides (both flat surfaces and shoulders) were marked in five spots (bud, mid-bud, middle, mid-stem, stem) that created a longitudinal line from the bud end to the stem end of the tuber.

1
No color, slight cell deformation

2
Light gray color, not severe but discoloration occurred

3
Dark grayish color, severity is medium, dark but not extreme

4
Dark gray/black color, severity is extreme

Figure 2-2. Blackspot bruise severity was rated on the darkest color observed on a scale from 1 to 4: 1= no color, 2=light gray color, not severe but discoloration occurred, 3=dark gray color, severity is moderate, dark but not extreme, 4=dark gray/black color, severity is extreme.

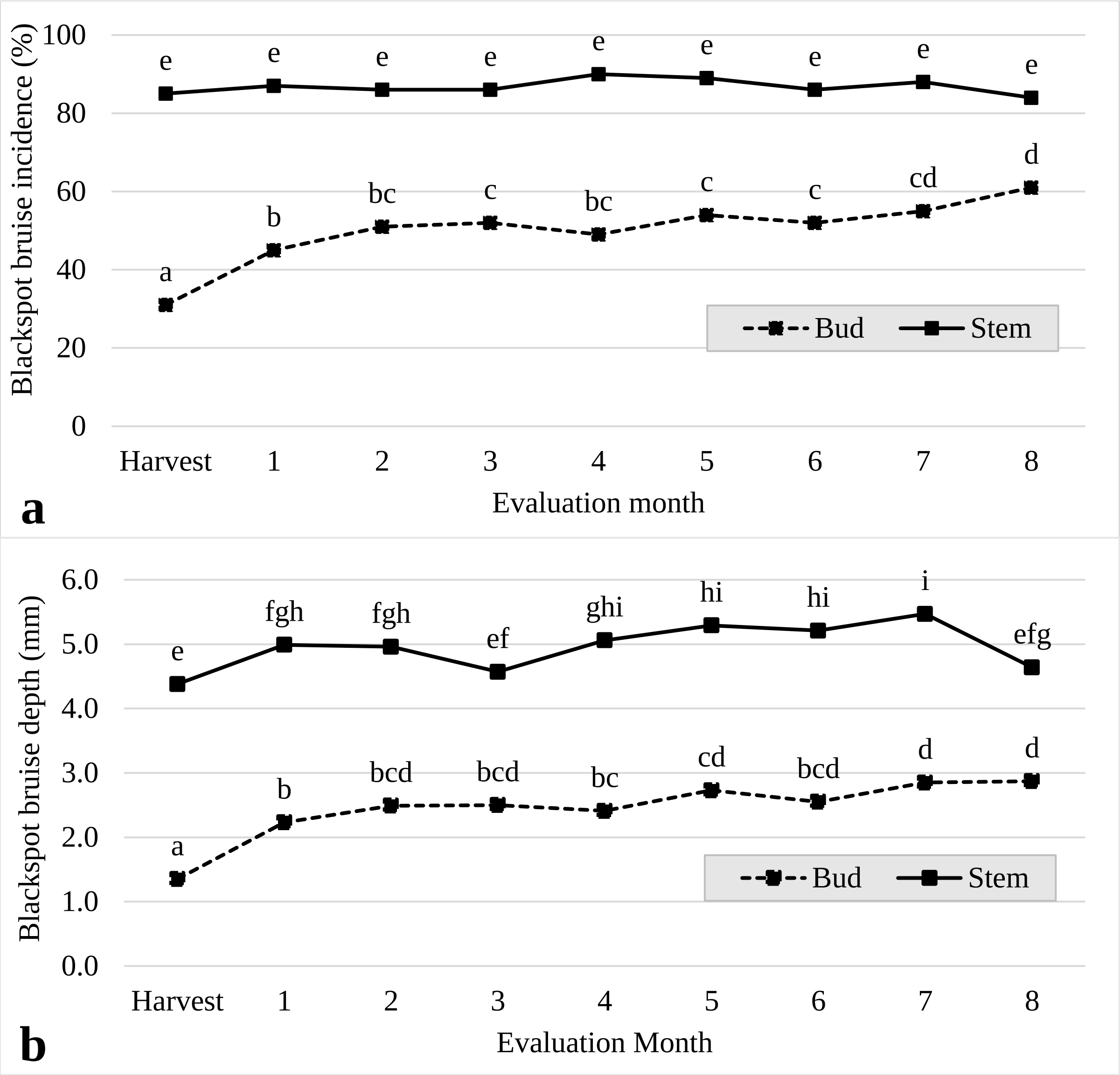

Figure 2-3. Tubers impacted at harvest (12.8°C) and development evaluated throughout storage: Effect of tuber end and evaluation month for bruise development a) blackspot bruise incidence and b) blackspot bruise depth. Results are means of two years. Values followed by the same letter are not significantly different (α<0.05) for each graph.

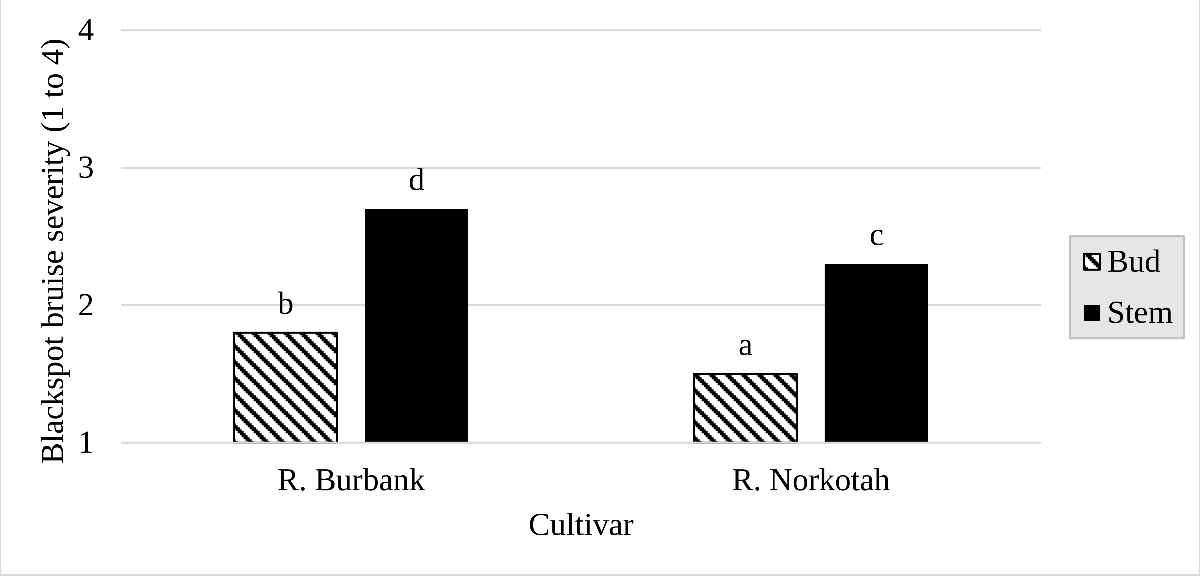

Figure 2-4. Tubers impacted at harvest (12.8°C) and development evaluated throughout storage: Effect of cultivar and tuber end for blackspot bruise severity. Blackspot bruise severity was rated on the darkest color observed on a scale from 1 to 4: 1= no color, 2=light gray color, not severe but discoloration occurred, 3=dark gray color, severity is moderate, dark but not extreme, 4=dark gray/black color, severity is extreme. Results are means of two years. Values followed by the same letter are not significantly different (α<0.05).

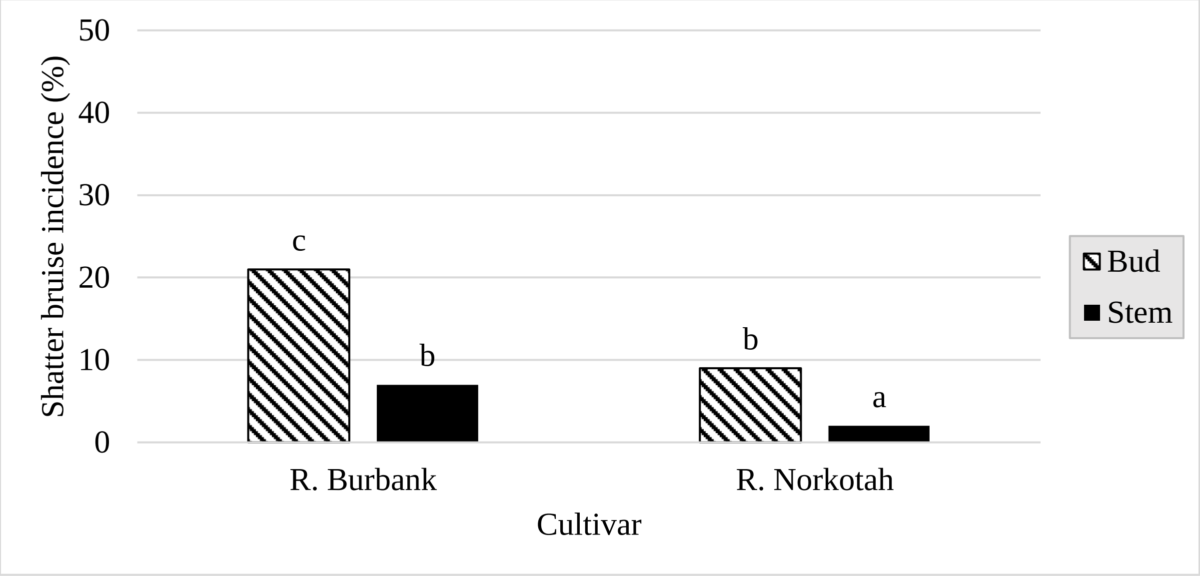

Figure 2-5. Tubers impacted at harvest (12.8°C) and development evaluated throughout storage: Effect of cultivar and tuber end for shatter bruise incidence. Results are means of two years. Values followed by the same letter are not significantly different (α<0.05).

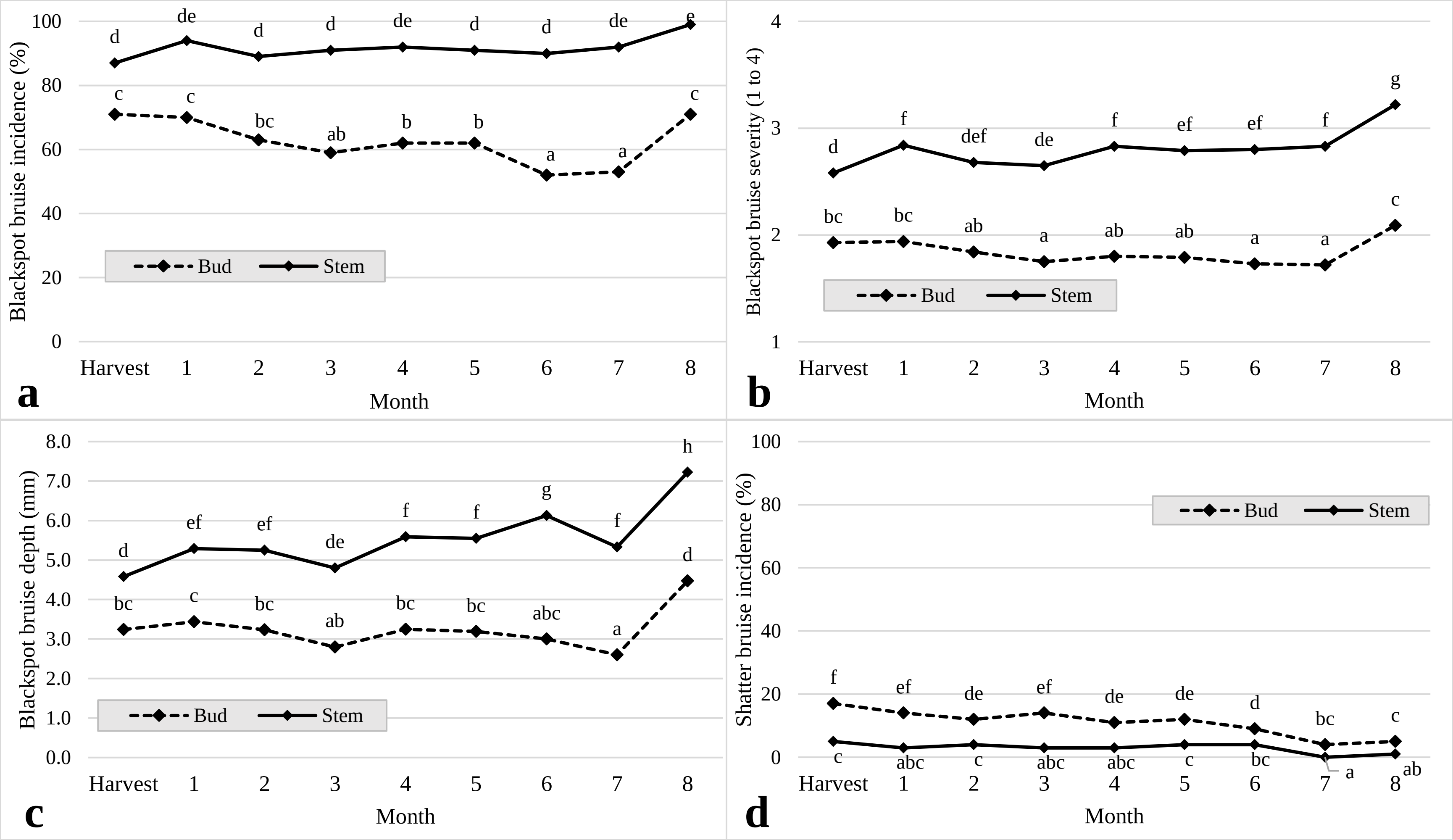

Figure 2-6. Tubers impacted at harvest (7.2°C) and impacted each month in storage (7.2°C): Effect of tuber end and evaluation month for bruise susceptibility a) blackspot bruise incidence and b) blackspot bruise severity c) blackspot bruise depth and d) shatter bruise incidence. Blackspot bruise severity was rated on the darkest color observed on a scale from 1 to 4: 1= no color, 2=light gray color, not severe but discoloration occurred, 3=dark gray color, severity is moderate, dark but not extreme, 4=dark gray/black color, severity is extreme. Results are means of two years. Values followed by the same letter are not significantly different (α<0.05) for each graph.

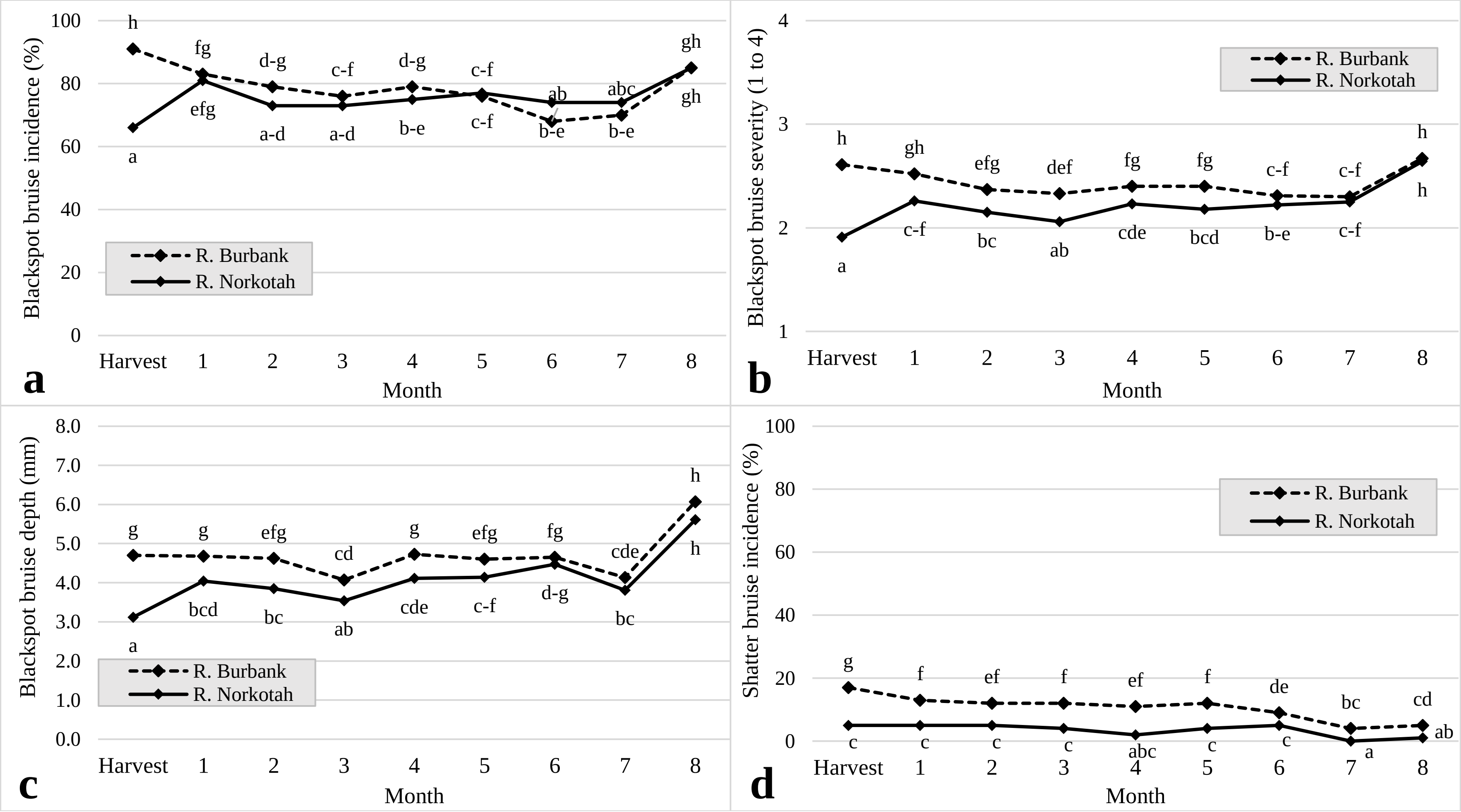

Figure 2-7. Tubers impacted at harvest (7.2°C) and impacted each month in storage (7.2°C): Effect of cultivar and evaluation month for bruise susceptibility a) blackspot bruise incidence and b) blackspot bruise severity c) blackspot bruise depth and d) shatter bruise incidence. Blackspot bruise severity was rated on the darkest color observed on a scale from 1 to 4: 1= no color, 2=light gray color, not severe but discoloration occurred, 3=dark gray color, severity is moderate, dark but not extreme, 4=dark gray/black color, severity is extreme. Results are means of two years. Values followed by the same letter are not significantly different (α<0.05) for each graph.

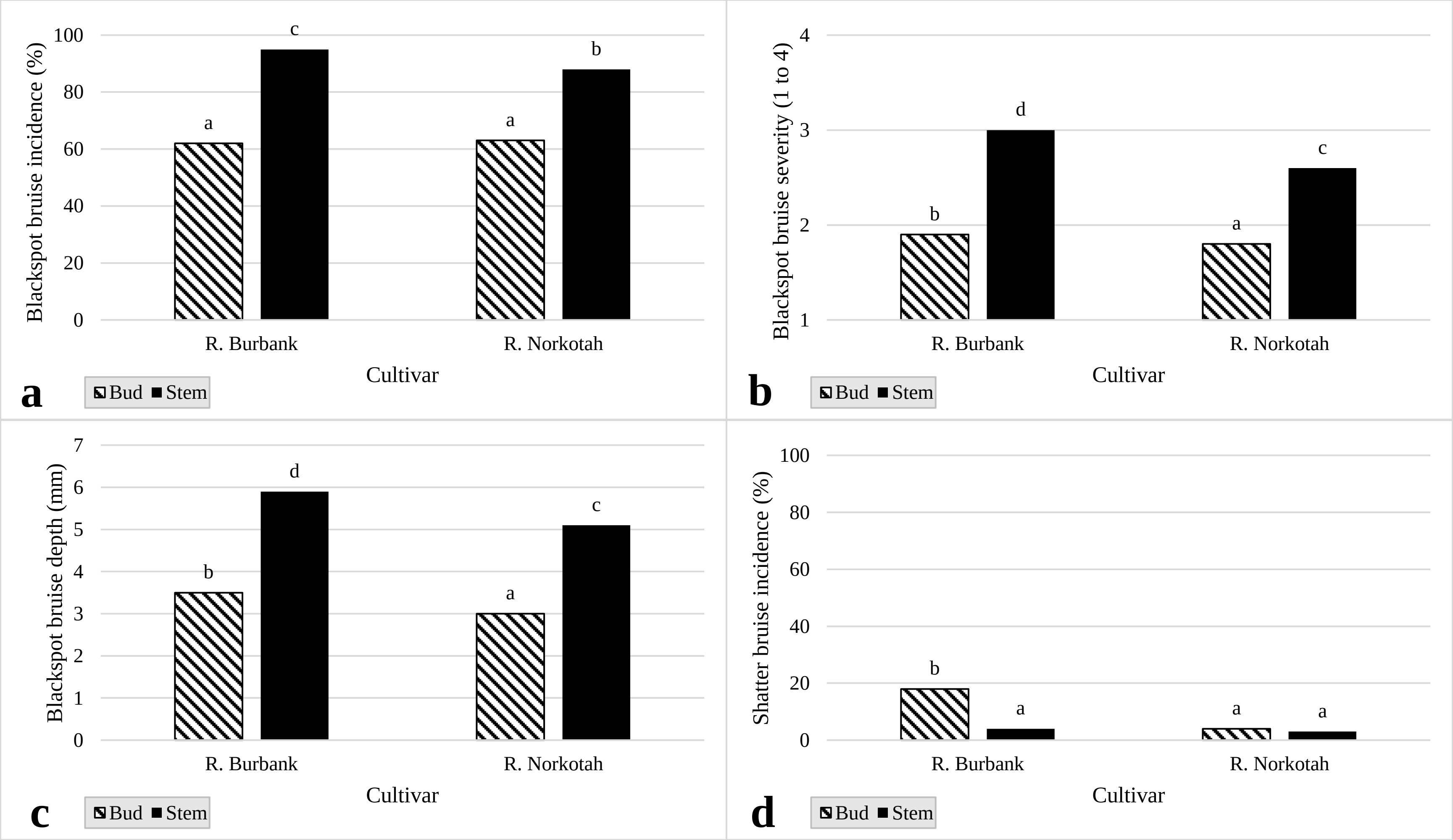

Figure 2-8 Tubers impacted at harvest (7.2°C) and impacted each month in storage (7.2°C): Effect of cultivar and tuber end for bruise susceptibility a) blackspot bruise incidence and b) blackspot bruise severity c) blackspot bruise depth and d) shatter bruise incidence. Blackspot bruise severity was rated on the darkest color observed on a scale from 1 to 4: 1= no color, 2=light gray color, not severe but discoloration occurred, 3=dark gray color, severity is moderate, dark but not extreme, 4=dark gray/black color, severity is extreme. Results are means of two years. Values followed by the same letter are not significantly different ($\alpha<0.05$) for each graph.

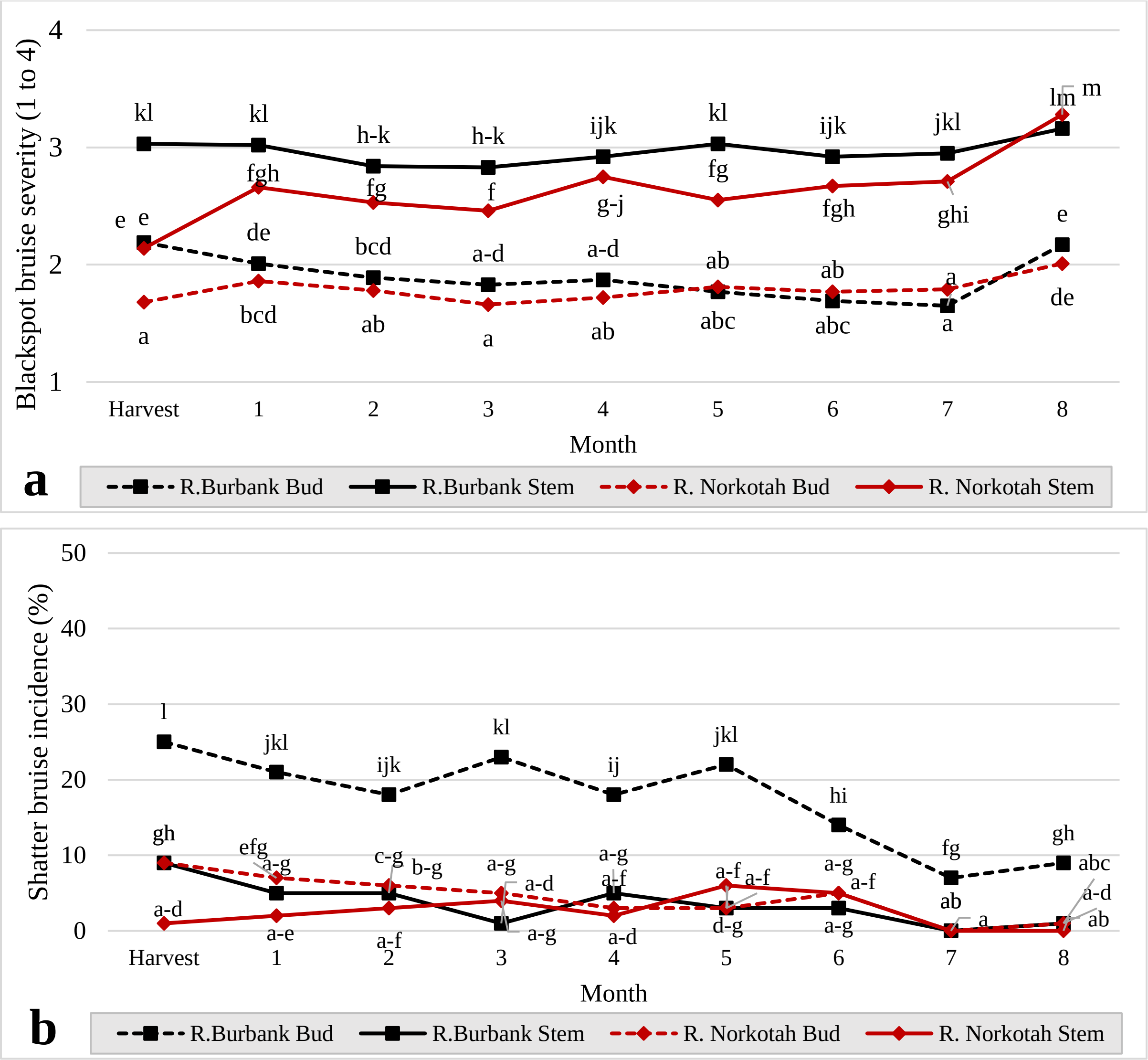

Figure 2-9. Tubers impacted at harvest (7.2°C) and impacted each month in storage (7.2°C): Effect of cultivar, tuber end and month for bruise susceptibility a) blackspot bruise severity and b) shatter bruise incidence. Blackspot bruise severity was rated on the darkest color observed on a scale from 1 to 4: 1= no color, 2=light gray color, not severe but discoloration occurred, 3=dark gray color, severity is moderate, dark but not extreme, 4=dark gray/black color, severity is extreme. Results are means of two years. Values followed by the same letter are not significantly different ($\alpha<0.05$) for each graph.

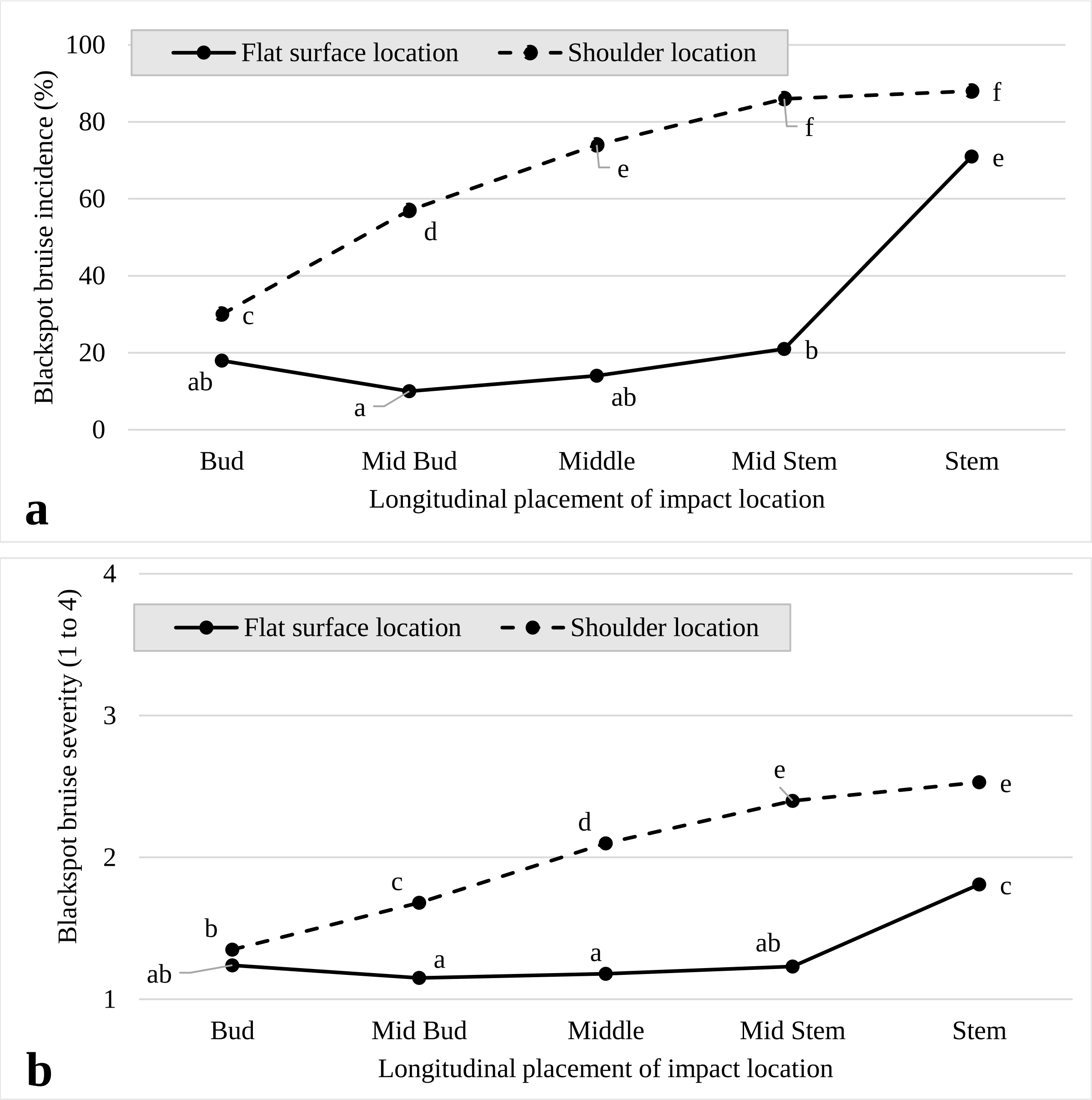

Figure 2-10. Russet Burbank impacted (12.8°C) on different locations of surface area: Effect of longitudinal placement and tuber side for a) blackspot bruise incidence and b) blackspot bruise severity. Blackspot bruise severity was rated on the darkest color observed on a scale from 1 to 4: 1= no color, 2=light gray color, not severe but discoloration occurred, 3=dark gray color, severity is moderate, dark but not extreme, 4=dark gray/black color, severity is extreme. Results are means of one storage season. Values followed by the same letter are not significantly different (α<0.05) for each graph.

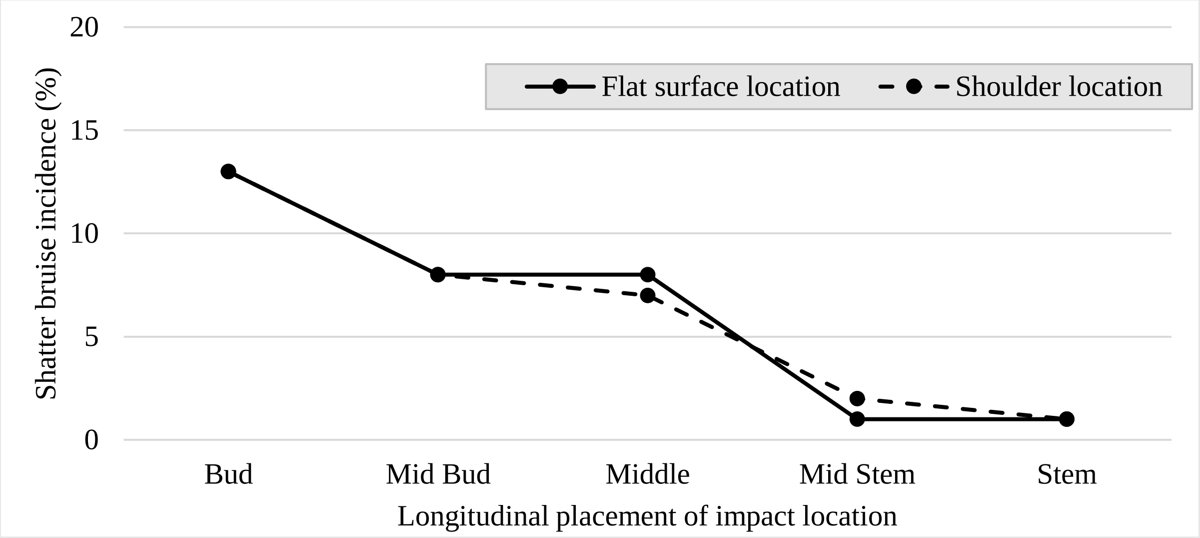

Figure 2-11. Russet Burbank impacted (12.8°C) on different locations of surface area: No significant effect between tuber ends and tuber sides for shatter bruise incidence (*P* = 0.89). Results are means of one storage season.

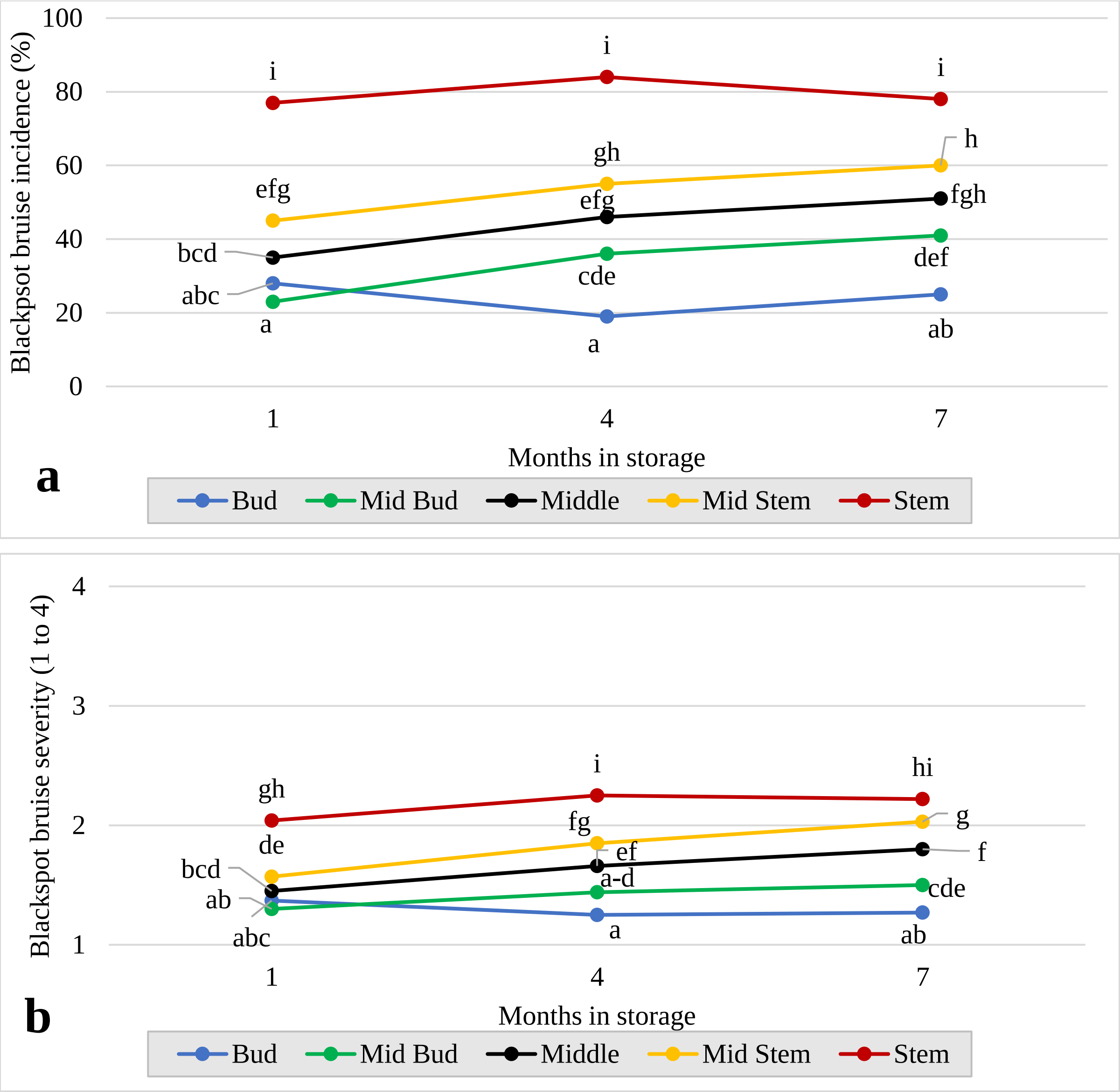

Figure 2-12. Russet Burbank impacted (12.8°C) on different locations of surface area: Effect of longitudinal placement and time in storage for a) blackspot bruise incidence and b) blackspot bruise severity. Blackspot bruise severity was rated on the darkest color observed on a scale from 1 to 4: 1= no color, 2=light gray color, not severe but discoloration occurred, 3=dark gray color, severity is moderate, dark but not extreme, 4=dark gray/black color, severity is extreme. Results are means of three experiments in one storage season. Values followed by the same letter are not significantly different (α<0.05) for each graph.

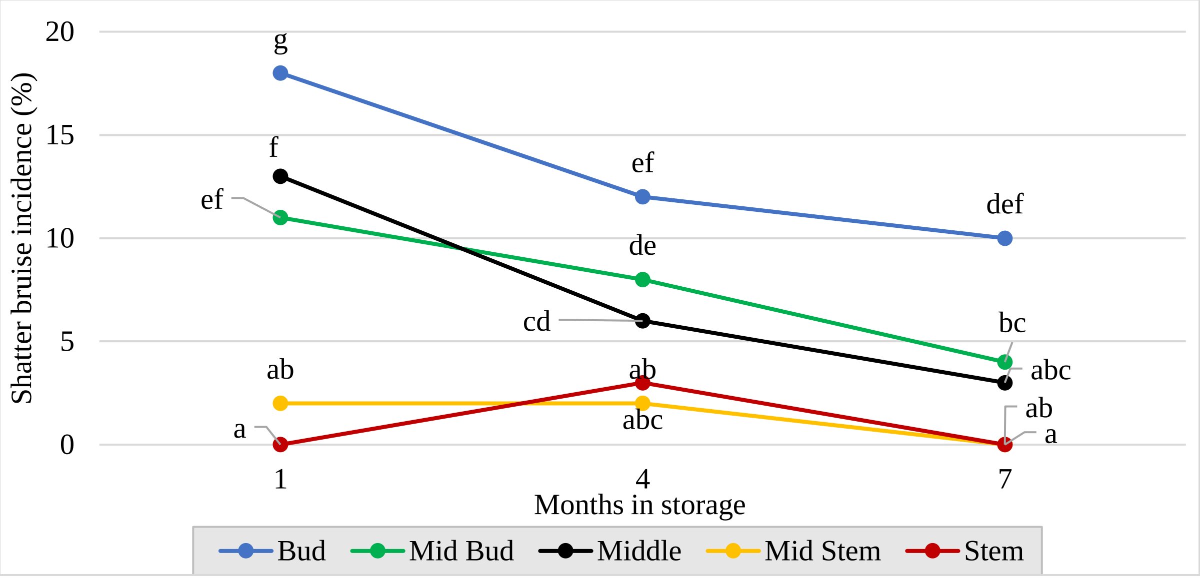

Figure 2-13. Russet Burbank impacted (12.8°C) on different locations of surface area: Effect of longitudinal placement and time in storage for shatter bruise incidence. Results are means of three experiments in one storage season. Values followed by the same letter are not significantly different ($\alpha<0.05$).

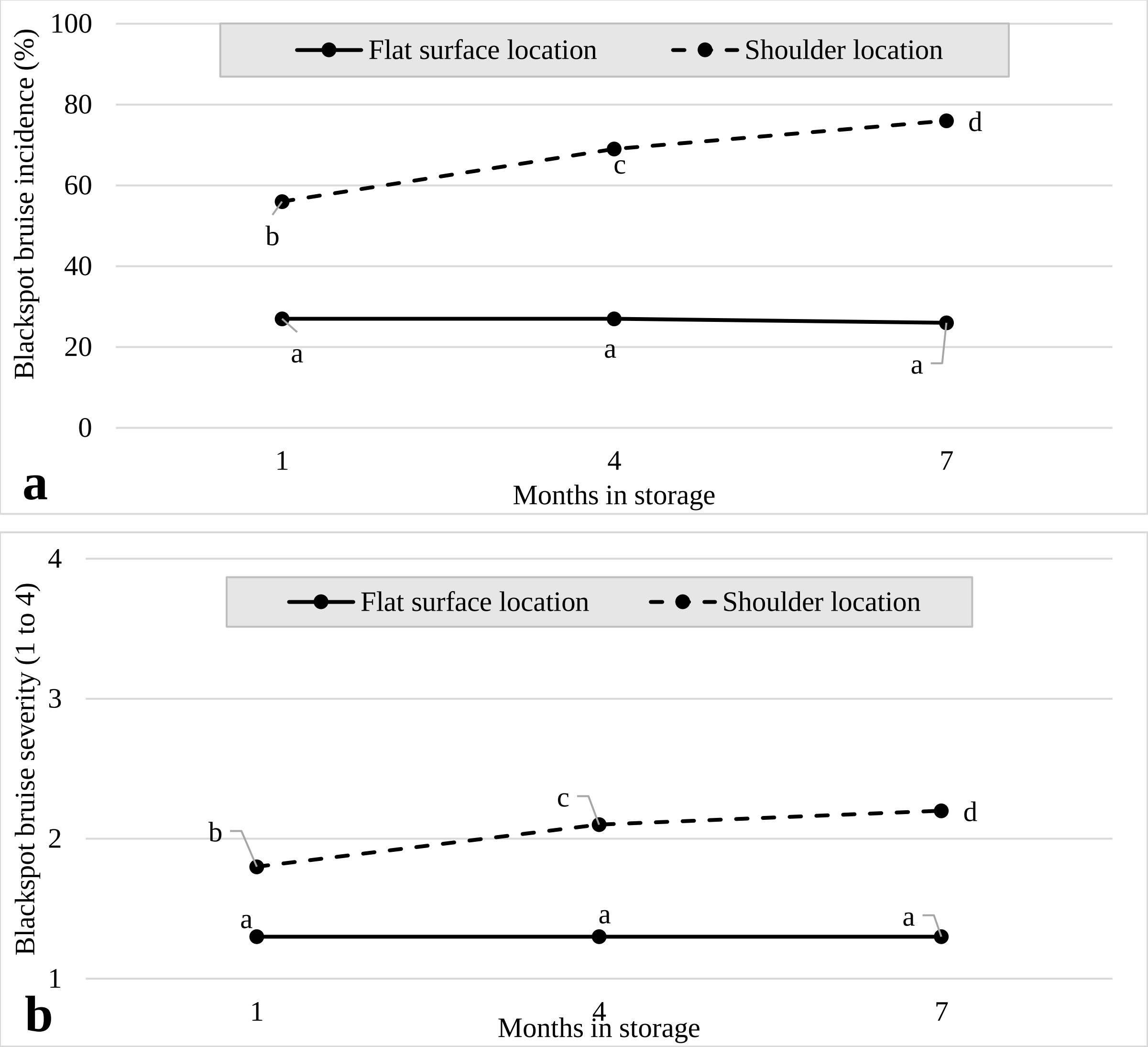

Figure 2-14. Russet Burbank impacted (12.8°C) on different locations of surface area: Effect of tuber sides and months in storage for a) blackspot bruise incidence, b) blackspot bruise severity. Blackspot bruise severity was rated on the darkest color observed on a scale from 1 to 4: 1= no color, 2=light gray color, not severe but discoloration occurred, 3=dark gray color, severity is moderate, dark but not extreme, 4=dark gray/black color, severity is extreme. Results are means of three experiments in one storage season. Values followed by the same letter are not significantly different (α<0.05) for each graph.

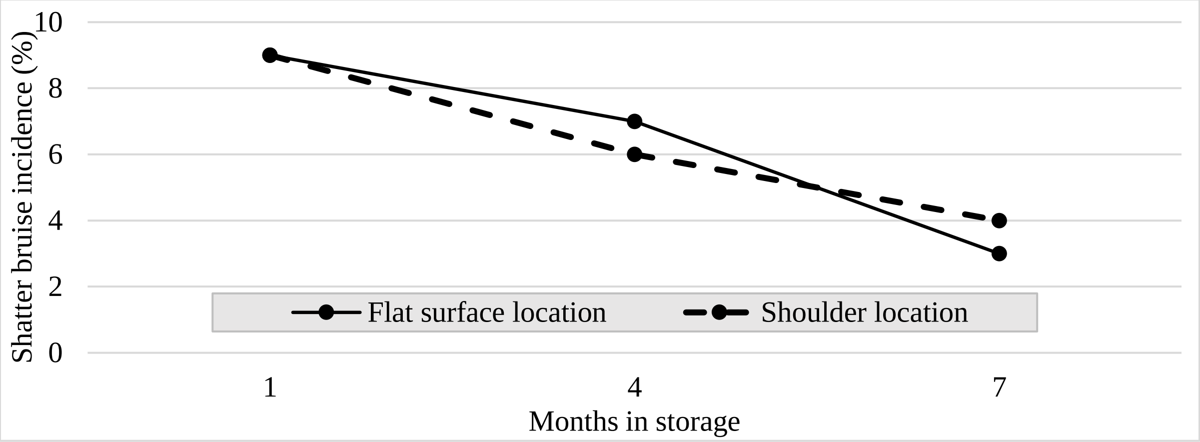

Figure 2-15. Russet Burbank impacted (12.8°C) on different locations of surface area: There was no significant effect between tuber sides and months in storage for shatter bruise incidence (*P* = 0.79). Results are means of three experiments in one storage season.

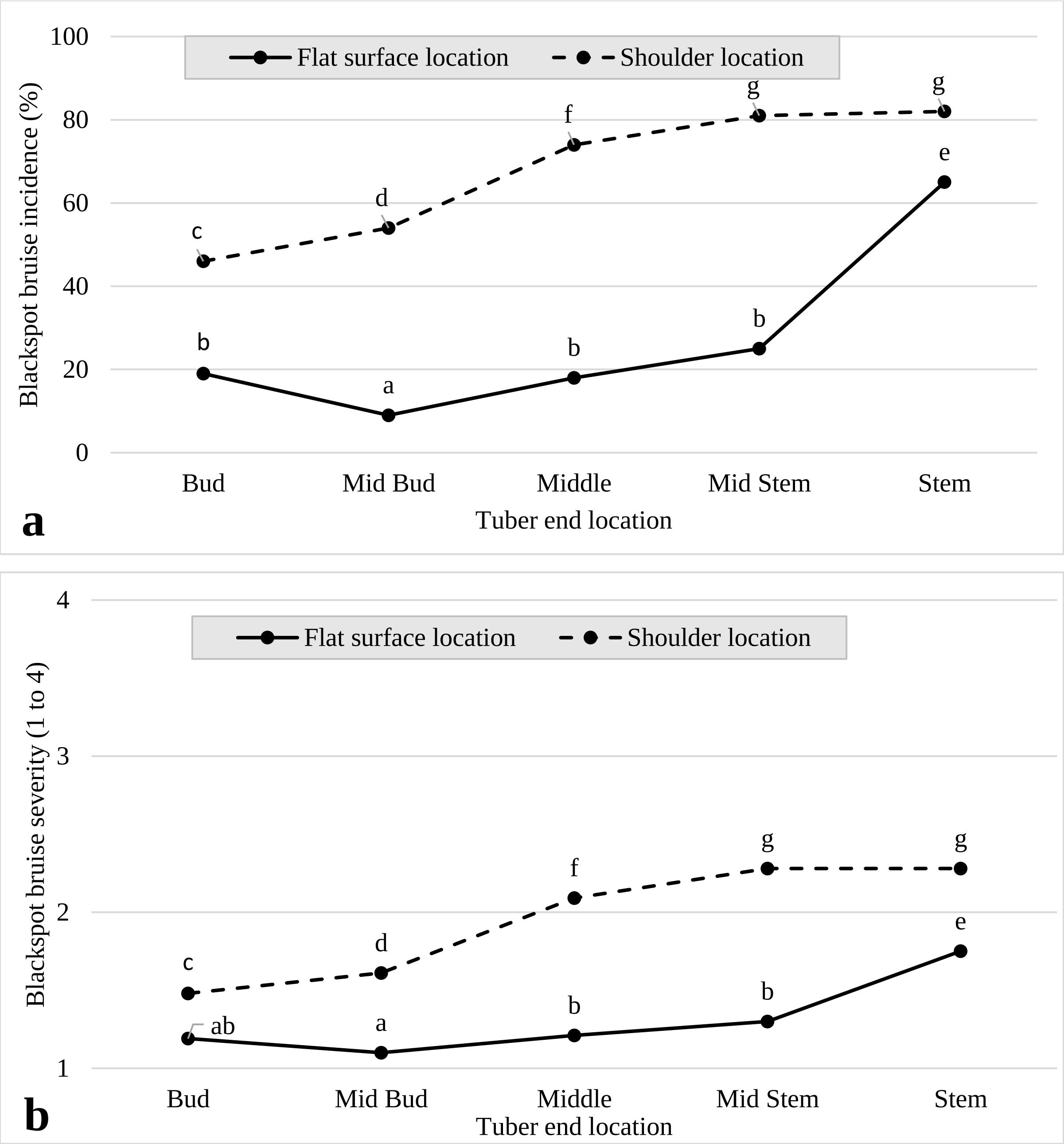

Figure 2-16. Russet Norkotah impacted (12.8°C) on different locations of surface area: Effect of longitudinal placement and tuber sides for a) blackspot bruise incidence and b) blackspot bruise severity. Blackspot bruise severity was rated on the darkest color observed on a scale from 1 to 4: 1= no color, 2=light gray color, not severe but discoloration occurred, 3=dark gray color, severity is moderate, dark but not extreme, 4=dark gray/black color, severity is extreme. Results are means of three experiments in one storage season. Values followed by the same letter are not significantly different (α<0.05) for each graph.

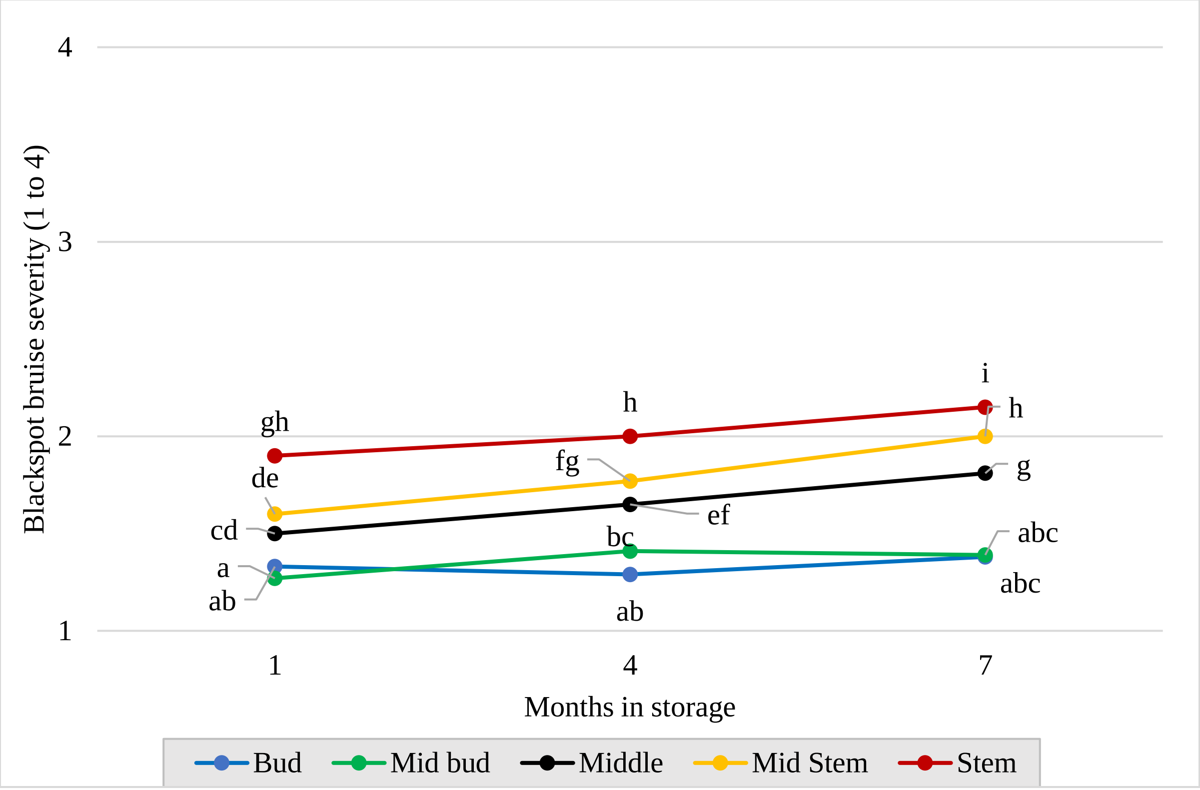

Figure 2-17. Russet Norkotah impacted (12.8°C) on different locations of surface area: Effect of longitudinal placement and time in storage for blackspot bruise severity. Blackspot bruise severity was rated on the darkest color observed on a scale from 1 to 4: 1= no color, 2=light gray color, not severe but discoloration occurred, 3=dark gray color, severity is moderate, dark but not extreme, 4=dark gray/black color, severity is extreme. Results are means of three experiments in one storage season. Values followed by the same letter are not significantly different (α<0.05).

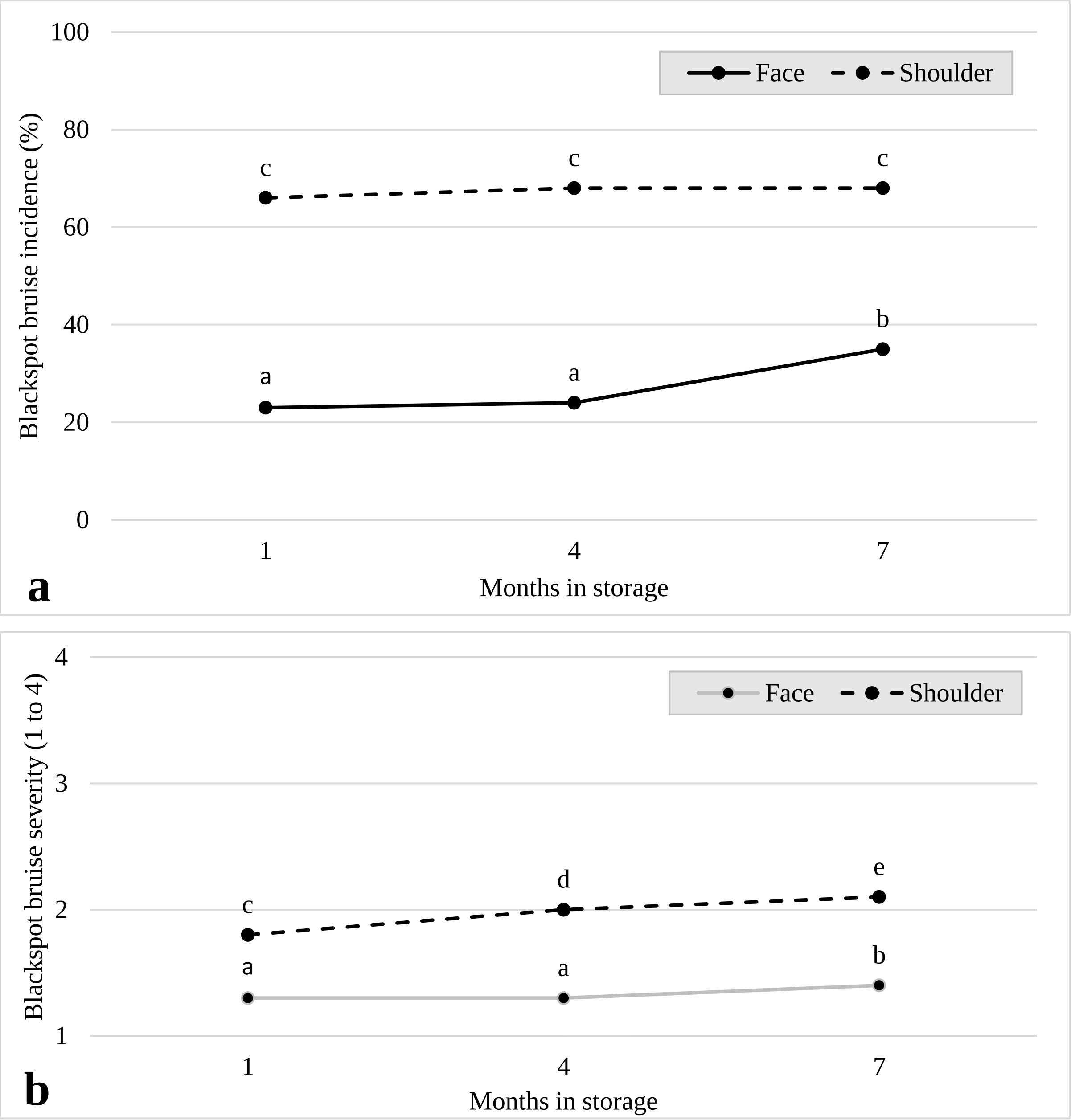

Figure 2-18. Russet Norkotah impacted (12.8°C) on different locations of surface area: Effect of tuber sides and months in storage for a) blackspot bruise incidence and b) blackspot bruise severity. Blackspot bruise severity was rated on the darkest color observed on a scale from 1 to 4: 1= no color, 2=light gray color, not severe but discoloration occurred, 3=dark gray color, severity is moderate, dark but not extreme, 4=dark gray/black color, severity is extreme. Results are means of three experiments in one storage season. Values followed by the same letter are not significantly different (α<0.05) for each graph.

Chapter 3: Development of Potato Bruises as Influenced by Cultivar, Impact Height, and Holding Temperature

Abstract

Handling of potatoes can result in impact injuries, with the two main types being blackspot and shatter bruise. The objective of this study was to examine the development of blackspot and shatter bruise over a 24 to 48-hour period as influenced by cultivar, impact height and holding temperature. Potato tubers (8.9°C pulp temperature) were bruised using a free-falling 100 g weight set at a height of 18 or 30 cm (Russet Burbank and Ranger Russet) and 30 cm for Russet Norkotah to deliver two uniform impacts on each end of the tuber. Bruised tubers were held at either 21.1°C or 8.9°C and evaluated after 1, 2, 3, 4, 5 and 24 hours. Peeled tubers were evaluated for incidence, color intensity, and depth of blackspot bruise and shatter bruise incidence. The change in flesh color at the impact site from pink to brown primarily occurred one to three hours after impact, and as a result the incidence of pink discoloration declined rapidly after that time. Over 70% of the total blackspot bruise incidence was observed after four hours, depending on impact force and cultivar. Likewise, the maximum extent of bruise depth (70%) tended to develop within five hours after impact. The bud end had lower overall blackspot bruise incidence, color intensity and depth and was slower to develop discoloration compared to the stem end. Shatter bruise incidence significantly increased from 15% at hour three to 18% by hour 5 and was 21% by hour 24. Rapid bruise assessment can be conducted between two to five hours for Russet Burbank, two to three hours for Russet Norkotah, and by one to two hours for Ranger Russet. This study confirms that fresh, developing bruises can be utilized as an early indicator of damage incidence in samples from handling operations.

Introduction

Physical impacts that occur in potato handling operations can result in bruises. These impacts occur when potatoes contact equipment components, change direction or drop from conveyor belts onto different surfaces (Bentini et al. 2006; Hyde et al. 1988). The two most common types of bruises are blackspot and shatter bruise. Blackspot bruising occurs when a tuber’s cell membranes are damaged, but the periderm remains unbroken (McGarry et al. 1996). Since the periderm is not damaged, the bruise cannot be seen without removing the periderm. Once the impact occurs, the intracellular membranes rupture causing a biochemical reaction to occur between polyphenol oxidase (PPO), tyrosine, and other substrates resulting in melanin formation that appears as a dark discoloration at the area of impact (Edgell et al. 1998; Vreugdenhil et al. 2007; Dean 1996). This reaction can take 48 hours or more to fully develop (Dwelle and Stallknecht 1976). Some research, such as Noble (1985), held tubers 10 days at room temperature (20°C) prior to evaluation of bruise to ensure full development. Unlike blackspot bruise, which deforms intracellular membranes, shatter bruise splits the cell walls of the damaged area and expands outward and deep into the tissue. Shatter bruise can be visually assessed as soon as damage occurs (Vreugdenhil et al. 2007; Hollingshead et al. 2020a). Shatter bruise can affect the skin quality because it results in large cuts and visible splitting of the skin, as well as creating storability issues (McGarry et al. 1996). Shatter bruised tissue can be slow to heal in storage (Thomson et al. 1995), have increased weight loss, and creates an entry point for pathogens to infect and cause storage diseases such as Fusarium dry rot, Pythium leak, or bacterial soft rot (Hollingshead et al. 2020b; Singh et al. 2021).

Both bruises can be logistically difficult to monitor during handling operations. From initiation (harvesting out of the ground) to completion of a handling operation, potatoes flow uninterrupted. Due to the time needed for blackspot bruises to develop and uninterrupted flow of potatoes, knowledge of bruise levels and adjustments to lower those levels cannot occur simultaneously. Rapid bruise detection methods have been examined to shorten the gap between taking samples from operations, evaluating for bruise, and adjusting equipment or conditions as needed (Thornton 1982; Beaver and DeVoy 1986; McRae and Melrose 1993; Olsen and Thornton 2017). It has been shown that flesh discoloration, beginning as a pink color, can be seen three to six hours after impact (Weaver et al. 1970). Laerke et al. (2002) found blended tuber tissue samples change pigment within 30 minutes, concluding bruise discoloration had the potential to develop in a short period of time. Thornton et al. (1973) also stated discoloration began six to 12 hours after impact and peaked at 24 hours, though they still recommend waiting six to 48 hours before assessing fully developed bruise levels from a sample. Time constraints for assessments result in a major lag between taking samples and adjusting equipment based on results (Olsen and Thornton 2017). Beyond monitoring bruise levels in operations, the United States Department of Agriculture (USDA) fresh market and processing inspection guidelines specify holding potatoes for 48 hours before any bruise inspections can be made (USDA 2012; USDA 2015).

Multiple research studies have shown that adjusting the holding temperature after impact can influence the time required for bruise development to occur. Warmer temperatures (up to 32.2°C) can reduce blackspot bruise development time from 48 hours to 6 hours after impact (Olsen and Thornton 2017). Thornton (1982) held impacted tubers at 35°C for 6 hours and determined that 80% of bruises had begun to develop by this time. Commercial ‘hot boxes’ have been used to accelerate bruise development for a 12-hour detection method for blackspot bruise (McRae and Melrose 1993). To easily detect shatter bruise, dye solutions have been used to improve the visibility of the bruise (Hollingshead, et al. 2020b; Beaver and DeVoy 1986; McRae and Melrose 1993). Beaver and DeVoy (1986) concluded colder dye solution temperatures resulted in 15-to-30-minute longer bruise development times. This study implied if the tuber pulp temperature was colder, development may be slower for blackspot and shatter bruise. Cold pulp temperature at time of bruising has been found to increase bruise susceptibility (Thornton et al 1973; Smittle et al. 1974; McGarry et al. 1996; Baritelle and Hyde 2001; Xie et al. 2020), but the timeline of bruise development at different storage temperatures is not well understood. Research has determined that temperature can influence how quickly bruises develop but there is a lack of information about the utilization of developing bruises (prior to full color development) for bruise detection.

It is well-known cultivars vary in bruise susceptibility. Biochemical components are one aspect that contributes to the variance in susceptibility between cultivars. Sabba and Dean (1994) found protein-bound tyrosine concentrations were higher and activity of proteinases were lower in bruise resistant cultivars whereas free tyrosine was highly correlated to the development of melanin-like pigments. Strehmel et al. (2010) found there were higher levels of succinate and fumarate with lower levels of aconitate in a blackspot bruise susceptible cultivar. Succinate, fumarate, and aconitate are related to the intracellular response due to mechanical stress or damage (Strehmel et al. 2010). One biochemical component that has been found to be related to the formation of melanin (a component of blackspot bruise) is PPO enzymes (Bachem et al. 1994; Sabba and Dean 1994; Corsini et al. 1992). Hsu et al. (1988) detected PPO differences in three cultivars. Not only is there variation in biochemical components among cultivars, but various parts of the tuber have been found to have differing biochemical components. The stolon (stem) end of the tuber is more susceptible to blackspot bruise than the apical (bud) end (McGarry et al. 1996). Corsini et al. (1992) also found free-tyrosine levels were different in cultivars and tuber ends and higher levels of free-tyrosine were correlated to blackspot bruise susceptibility. Tyrosine has been reported to be 20 to 40% more concentrated in the stem end of the tuber compared to bud end (Reeve et al. 1969). Biochemical components involved in bruise development can vary between cultivars and between tuber ends, and the components are altered within the first 24 hours after impact (Partington et al. 1999). Concentrations of biochemical components could be different among cultivars and between tuber ends suggesting bruise development could be distinct and indicates the need to provide rapid bruise detection methods that are cultivar specific.

One of the major adjustments made during the harvest and handling process that affects bruise development is impact height as tubers transition from one surface to another. Lowering drop heights in a handling operation has been well-documented to minimize bruise (Corsini et al. 1999; Mathew and Hyde 1997; Partington et al. 1999; Thornton and Bohl 1995; Xie et al. 2020). Higher impact forces can result in shatter bruise, while lower impacts can cause blackspot bruises (McGarry et al. 1996). Noble (1985) found long impact durations and low loading velocities will produce blackspot bruise whereas short impact durations and high loading velocities will produce more shatter bruise. Although research has examined drop heights and variables associated with drop heights as contributing factors to bruise susceptibility, there is a gap in knowledge about how drop height may affect the time it takes for a bruise to develop. This information could aid in the ability to use developing bruises to assess mild or severe physical impacts in a handling operation.

The objective of this study was to examine the rate of bruise development for the first five hours after impact and additionally at 24 and/or 48 hours. Bruise development of three cultivars, Russet Burbank (R. Burbank), Russet Norkotah (R. Norkotah), and Ranger Russet (Ranger R.) was examined. These cultivars differ in blackspot and shatter bruise susceptibility. Russet Burbank, which is used in the fresh and processing markets, has been extensively researched and is considered intermediately (Corsini 1996) or moderately (Love et al. 1994) susceptible to blackspot bruising. Russet Burbank susceptibility to shatter bruise is relatively high (Spear et al. 2017). Russet Norkotah, a major cultivar used in the fresh market, is relatively resistant to blackspot and shatter bruise (Spear et al. 2017). Ranger Russet, primarily used in the processing market, is known for being more susceptible to blackspot bruise than R. Burbank (Love et al. 1998) and considered moderately susceptible to shatter bruise (Thornton and Olsen 2016).

Methods and Materials

There were four main objectives for this study. The first objective was to examine how bruise developed in the first five hours after impact compared to 24 or 48 hours after impact. This objective was examined in a meta-analysis (Table 3-1). The second objective examined how quickly each cultivar developed bruises following impact. Each cultivar was examined in a separate experiment. The third objective was to determine if impact height influences how quickly bruises develop. This objective was carried out in experiments with R. Burbank and Ranger R. The final objective was to understand how quickly bruise developed at a typical storage temperature. This was carried out in an experiment with R. Burbank. Table 3-1 describes all experimental treatments.

Each experiment's treatments included a destructive evaluation of bruise development after impact. Blackspot bruise color intensity, depth and incidence and shatter bruise incidence were evaluated as measurements of bruise development, as described below. All tubers were impacted at 8.9°C pulp temperature, a common storage temperature. After impact at either 18 cm (Ranger R. and R. Burbank) or 30 cm (Ranger R., R. Burbank and R. Norkotah), tubers were stored at 21.1°C (room temperature) for 1, 2, 3, 4, 5, and 24 hours prior to evaluation. An additional experiment was conducted with R. Burbank tubers stored at 8.9°C after impact, evaluated at the same hourly interval and included a supplementary evaluation at 48 hours. Experiments were conducted in the 2018-19 and 2019-20 storage seasons excluding experiments with Ranger R., which were only conducted in the 2019-20 storage season. Each experiment was repeated twice per storage season for a total of four trials per experiment (Table 3-1). Each trial had a 30-tuber sample per replicate (three replicates per treatment) in 2018. A power test (power=0.95) was conducted, and the sample size was reduced to a 15-tuber sample per replicate for 2019.

Potatoes used in these experiments were harvested from the 2018 and 2019 crop grown at the University of Idaho Kimberly Research and Extension Center (KREC). Certified R. Burbank seed potatoes were planted at the KREC on April 24, 2018. Plants were grown under University of Idaho recommendations for fertility, irrigation, and pest control. Plants were flail-mowed on September 5, 2018 and harvested September 20, 2018. Harvested tubers were cured at 12.8°C for two weeks and stored at 8.9°C with 95% relative humidity (RH) at the KREC storage facility until experiments were conducted. Russet Norkotah 278 potatoes were commercially obtained February 13, 2019 and placed into storage at the KREC facility at 8.9°C (95% RH) until impacted. Tubers received a thermal application of the sprout inhibitor isopropyl (3-chlorophenyl) carbamate (chlorpropham; Aceto Agricultural Chemicals Corporation) at 22 ppm on November 20, 2018. Certified seed for R. Burbank, R. Norkotah 278, and Ranger R. were planted at KREC on April 25, 2019, flail-mowed on September 12, harvested on September 24, 2019, and followed the previous year's curing and storage procedures. Tubers received a thermal application of chlorpropham (22 ppm) on November 26, 2019.

Bruise impact protocols

Washed tubers (170 to 450 g) were marked on predetermined locations void of obvious defects. The marked spots allowed for ease of knowing the location of the impact and to facilitate evaluations. Tubers were impacted using a device that dropped a 100 g steel weight from an 18 cm or 30 cm height to deliver a uniform impact on a stationary tuber. Tubers were impacted on two locations on the apical end and two locations on the stem end of each tuber. Preliminary data showed no significant differences between the two impacts sites on each end of the tuber, therefore in 2019-20 experiments only one spot on each end was impacted.

Evaluation of bruise development

The marked and impacted areas were peeled using a standard vegetable peeler (Kuhn Rikon Original Swiss Peeler, Switzerland) and evaluated for blackspot bruise color intensity, bruise depth, incidence of blackspot bruise, and incidence of shatter bruise. Blackspot bruise color intensity was rated on the darkest color observed on a scale from 1 to 5: 1= no discoloration, 2=pink, 3=light brown, 4=dark brown, and 5=black discoloration (Figure 3-1). Blackspot bruise depth was evaluated by recording the number of slices removed by the peeler until no color was present. Preliminary data determined the average thickness of each slice to be 1.27 mm. Blackspot bruise depth was calculated as the number of peels * 1.27 mm. Presence for shatter bruise was determined if there was a fracture in the cell wall visible after the first layer (1.27 mm) of the periderm was removed. Incidence of blackspot bruise and shatter bruise was calculated by the presence or absence of bruise and calculated as a percentage of the impacted areas showing a bruise.

Statistical Analysis

Blackspot bruise severity, bruise depth, blackspot bruise incidence and shatter bruise incidence were analyzed using the analysis of variance (ANOVA) procedures in R (RStudio, package car version 3.0-9, 2020; Fox and Weisberg 2019). A meta-analysis was compiled for all experiments examining bruise development in a 24-hour period. Experiment, cultivar, impact height, and evaluation temperature were added as random variables in each linear model for each measured variable. Hours after impact and tuber end were selected as main effects in the models. This analysis was conducted to give overall insights on how bruises develop in a 24-hour period and fulfill objective one. For each experiment, a mixed-effect model was fitted where hours after impact, tuber end, and the interactions were considered fixed effects. Year and trial for all variables in each experiment showed significant interactions but showed similar trends, so year and trial were modeled as random effects. Shatter bruise incidence was combined from three trials with the cultivars R. Burbank and R. Norkotah evaluated after holding at 21.1°C after impact. Correlations between blackspot bruise color intensity and bruise depth were computed using the Spearman rank correlation (RStudio, package PerformanceAnalytics version 2.0.4, 2020; Peterson and Carl 2020). All trials' significant differences between means for response variables were compared at alpha of 0.05 by estimated marginal means procedures (RStudio, package emmeans version 1.6.1, 2020; Length 2021).

Results

Bruise development in a 24-hour period: Meta-analysis

All blackspot bruise variables examined in the meta-analysis were significant for hours after impact and tuber end (Table 3-2). A meta-analysis is a way to combine data from a series of independent studies with variability in results to provide a high level of confidence of an answer to a specified research question (Mikolajewicz and Komarova 2019). Blackspot bruise incidence, color intensity rating, and blackspot bruise depth significantly ($P<0.0001$) increased with hours after impact. Four hours after tubers were impacted, 70% of impacted areas that would exhibit blackspot bruises at hour 24 were visible. In the first two hours after impact, 89% of developing bruises had a pink discoloration, but by hour three, the pink discoloration began to turn brown or black (Figure 3-2). The time course and extent of bruise development was dependent on the tuber end ($P<0.0001$). The stem end developed a significantly higher incidence of blackspot bruises compared to the bud end, and those bruises were of a darker color intensity and deeper depth (Table 3-2). The stem end also developed blackspot bruises earlier within the first five hours after impact compared to the bud end (Figure 3-3). Hours after impact and tuber end were the significant ($P<0.0001$) sources of variance for shatter bruise incidence. The interaction between hours after impact and tuber end was not significant meaning both ends responded similarly for each hour examined (Table 3-2; *P*=0.96). Shatter bruise incidence increased from 15% at hour three to 18% by hour 5 and was 21% by hour 24 (Table 3-2). The bud end had higher shatter bruise incidence (21%) than the stem end (13%; Table 3-2).

The following sections will go in depth on the results of bruise development at different impact heights (18 or 30 cm) for R. Burbank, 30 cm impact height for R. Norkotah, 18 and 30 cm impact heights for Ranger R., and bruise development at 8.9°C after impact for R. Burbank.

Effect of impact height on bruise development at 21.1°C

Bruise development in R. Burbank for 18 cm impact height: Experiment 1

Blackspot bruise incidence increased from 22% at hour one to 52% by hour five. There was an additional increase in incidence to 72% by hour 24 (Table 3-3). Therefore, 72% of all bruises that eventually appeared by hour 24 were visible by hour five and 28% of the impacts did not discolor after 24 hours. Depth and color intensity had a high spearman rank correlation (r=0.92) since both variables increased incrementally with time after impact (Table 3-3). As depth of the bruise increased hourly (0.9 mm at hour one to 3.9 mm by hour 24), the color intensity increased (1.2 at hour one to 3.3 color intensity rating by hour 24; Table 3-3). The bud end had significantly (*P*<0.0001) lower blackspot bruise incidence (29%) than the stem end (62%). Color intensity and depth was lower (*P*<0.0001) on the bud end (1.5 rating; 1.4mm, respectively) compared to the stem end (2.3 rating; 3.2mm, respectively; Table 3-3). By hour two, 48% of impacted areas exhibited visible blackspot bruises on the stem end, whereas the bud end had 19% visible bruises (Figure 3-4). The stem end also developed deeper and darker bruises, and these bruises developed quicker than the bud end (Figure 3-4). Shatter bruise incidence ranged from 6% to 10% and was not significantly affected by the hours after impact (*P*=0.10; Table 3-3). Shatter bruise had higher (*P*<0.0001) incidence on the bud end (12%) than the stem end (4%).

Bruise development in Russet Burbank for 30 cm impact height: Experiment 2

The first trial in 2018 only examined the first five hours after impact (hour 24 was not examined); therefore, data for hour 24 is the least squared means of the other three trials. Blackspot bruise incidence increased from 44% to 96% from hour one to hour 24 (Table 3-4). Color intensity rating was not significantly different the first two hours (1.5 and 1.6 rating, respectively), but became darker from hour 3 to hour 24 (2.0 to 4.3 rating, respectively; Table 3-4). Between hour one and hour 24, blackspot bruise depth also significantly increased from 1.9 to 5.8 mm (Table 3-4). There was a high Spearman rank correlation between the color intensity rating and depth of blackspot bruises (r=0.88). The stem end had higher incidence, color intensity, and depth for blackspot bruises, and the bud end had higher shatter bruise incidence (Table 3-4). Shatter bruise incidence was not significantly different by hours after impact (P=0.13) ranging between 23 and 29% (Table 3-4). The bud end developed blackspot bruises slower than the stem end and no significant differences were observed from hour one until hour three for incidence, color intensity and depth, whereas the stem end had significant differences from hour one to hour two and increased at a faster rate within those first five hours (Figure 3-5).

Bruise development in R. Norkotah for 30 cm impact height: Experiment 3

Blackspot bruise incidence increased from 23% to 84% from hour one to hour 24 (Table 3-5). Color intensity rating incrementally increased each hour from 1.2 at hour one to 3.9 by hour 24 (Table 3-5). Between hour one and hour 24, blackspot bruise depth significantly (P<0.0001) increased from 1.0 to 4.5 mm (Table 3-5). There was a high Spearman rank correlation between the color intensity rating and depth of blackspot bruises (r=0.94). As discoloration increased, the bruises penetrated deeper into the tissue. The stem end showed increased incidence, color intensity, and depth for blackspot bruises, and increased shatter bruise incidence compared to the bud end (Table 3-5). Translucent stem ends were observed in Russet Norkotah (data not shown) which may explain the higher shatter bruise incidence on the stem end (15%) compared to the bud end (12%). Shatter bruise incidence was significantly affected by time after impact (P=0.01) ranging between 11% and 18%, but these differences did not follow a linear pattern, indicating that variance was more likely due to tuber sample variability than bruise development (Table 3-5). The stem end developed blackspot bruises at an increased rate within the first five hours compared to the bud end (Figure 3-6).

Bruise development in Ranger R. for 18 cm and 30 cm impact height: Experiment 4

Ranger R. impact tests were conducted on the same day in October 2019 and in May 2020; therefore, bruise development was compared at 18 and 30 cm impact heights. There was significantly (P<0.0001) lower blackspot bruise incidence, color intensity, depth, and shatter bruise incidence for tubers impacted at an 18 cm impact height compared to 30 cm impact height (Table 3-6). Impact height did not alter how blackspot bruise incidence or color intensity developed in Ranger R., with the exception that bruise depth increased within the first two hours at the 30 cm impact height whereas development from the 18 cm impact height did not increase until hour three (Figure 3-7). In the first hour after impact, 84% of the impacted areas exhibiting discoloration were pink, while the remaining 16% were brown or black. By hour two, 52% of the bruises exhibited pink discoloration with the remaining bruises turning brown or black by this time (Figure 3-8).

Averaged across impact heights and tuber ends, blackspot bruise incidence increased from 50% at hour one to 70% by hour five and increased to 89% by hour 24 (Table 3-6). Blackspot bruise color intensity rating was 1.6 at hour one and by hour three it was 3.0 rating. By hour 24, the color intensity was extreme with an average rating of 4.0, a dark brown bruise (Table 3-6). Blackspot bruise depth increased a total of 3.0 mm from hour one to hour 24 (Table 3-6). The bud end had significantly (*P*<0.0001) lower blackspot bruise incidence (45%) compared to the stem end (89%; Table 3-6). Color intensity and depth was significantly (*P*<0.0001) lower on the bud end (1.9 rating; 2.0 mm) compared to the stem end (3.3 rating; 4.6 mm). By hour one, blackspot bruise incidence was 76% on the stem end, whereas the bud end had 24% incidence at this time (Figure 3-9). The stem end developed deeper and darker bruises, and these bruises developed at an increased rate compared to the bud end (Figure 3-9). Shatter bruise incidence ranged from 6% to 9% and hours after impact was not significantly different (*P*=0.71; Table 3-6). Shatter bruise (*P*<0.0001) incidence was higher on the bud end (15%) than on the stem end (1%).

Effect of impact height on bruise development at 8.9°C

Bruise development in Russet Burbank for 18 cm impact height: Experiment 5

This experiment was conducted twice in the 2019-20 storage season and examined holding Russet Burbank from two drop heights at a common storage temperature (8.9°C) after impact. Blackspot bruise incidence increased in the first five hours from 10 to 32%. Blackspot bruise incidence significantly increased to 60% by hour 24 and then significantly increased to 68% by hour 48 (Table 3-7). The color intensity rating ranged from 1.1 to 1.5 during the first five hours but continued to significantly increase to a rating of 3.0 by hour 24 and significantly increased an additional ½ rating scale by hour 48 (3.5 rating; Table 3-7). Blackspot bruise depth was shallow the first five hours after impact (0.4 to 1.6 mm) but doubled in depth by hour 24 (3.0 mm) and then increased another to 3.7 mm by hour 48 (Table 3-7). The bud end had significantly (*P*<0.0001) lower blackspot bruise incidence (20%) compared to the stem end (46%). Color intensity and depth were lower (*P*<0.0001) on the bud end (1.5 rating; 0.9 mm) than on the stem end (2.2 rating; 2.3 mm). Pink discoloration peaked at hour five, making up 63% of the developing bruises. At hour 24, the pink discoloration was only 2% of the visible discoloration as most of the bruises were turning brown or black (Figure 3-10). Blackspot bruise incidence and depth developed at a slower rate on the bud end compared to the stem end for blackspot bruise incidence and depth, but at hour 24 the bruises on each end were similar to hour 48 (Figure 3-11). Blackspot bruise color intensity on the bud end was still developing from hour 24 to hour 48, but the stem end was not significantly different from hour 24 to 48 (Figure 3-11). Shatter bruise incidence ranged from 2% to 6% and hours after impact were not significantly different (*P*=0.24; Table 3-7). A higher shatter bruise (*P*<0.0001) incidence was observed on the bud end (7%) than on the stem end (1%).

Bruise development for 30 cm impact height: Experiment 6

Blackspot bruise incidence increased in the first 24 hours after impact (39 to 88%) then leveled off by hour 48 (92%; Table 3-8). The color intensity rating ranged from 1.4 to 2.1 during the first five hours of development but significantly increased to a rating of 3.9 by hour 24 and increased again by hour 48 (4.3 rating; Table 3-8). Blackspot bruise depth increased for hours after impact and continued to increase to hour 48 (2.0 to 6.5 mm). The bud end had significantly (P<0.0001) lower blackspot bruise incidence (44%) than the stem end (65%). Color intensity and depth was lower (P<0.0001) on the bud end (1.9 rating; 2.7 mm) than on the stem end (2.5 rating; 3.8 mm; Table 3-8). Pink discoloration peaked at hour three (making up 93% of developing bruises), but by hour 24 the pink discoloration was completely gone (Figure 3-12). Blackspot bruise on the bud end developed at a slower rate compared to the stem end, although the bud end reached peak incidence by hour 24 (Figure 3-13a). Blackspot bruise color intensity and depth on the bud end was still developing from hour 24 to hour 48, but the stem end was not significantly different between these time evaluations (Figure 3-13). Shatter bruise incidence was significantly different (P<0.0001) between hourly evaluations ranging between 18% and 27%, but these differences did not follow a linear pattern indicating variance was likely due to tuber sample variability (Table 3-8). Shatter bruise (P<0.0001) incidence was higher on the bud end (28%) than on the stem end (18%).

Discussion

The development of blackspot bruise is an enzymatic oxidation reaction. Previous studies have identified reactions involved in the biosynthesis of melanin as the brown/black pigments visible which are considered a blackspot bruise (Stevens et al 1998; Partington et al. 1999; Adams and Brown 2007). An overview of how this reaction occurs (Lerner and Fitzpatrick 1950) is as follows: tyrosine in the presence of tyrosinase (also known as PPO, phenolase, catechol oxidase, monophenol oxidase, cresolase, and catecholase; Whitaker 1995) and molecular oxygen is oxidized to form dihydroxyphenyl l-alanine (dopa). Dopa is then oxidized to form dopa-quinone, which undergoes a cyclization reaction to form leuco compound. The leuco compound is then oxidized resulting in hallachrome formation, a red colored substance, which is the first visible color of the reaction that forms melanin. Hallachrome undergoes decarboxylation and rearrangement to form 5,6-dihydroxyindole. This resulting indole is rapidly oxidized to indole-5,6-quinone, which then polymerizes to form melanin resulting in a dark brown or black color. The initial pink discoloration we observed in this study is assumed to be the beginning of the visual cellular disruption corresponding to the previous research. This coincides with Partington et al. (1999) who concluded melanin production begins within one hour after an impact and Strehmel et al. (2010) concluded when a potato undergoes mechanical stress or impact, biochemical properties change within the impacted tissue between 0.5 and 24 hours. Once the intracellular membranes have been disrupted and the associated compounds had as little as one hour to react, a pink discoloration begins to be visible. As time progresses these reactions continue and within three hours cell death is initiated (Partington et al. 1999). Partington et al. (1999) also concluded PPO experiences a subcellular redistribution 12 hours after impact around the same time cellular membranes collapse. It is believed the blackspot formation coincides with cell death as melanin production may effectively discolor the intracellular compounds inhibiting their function (Partington et al. 1999). This would coincide with the results observed within this study.

Our study showed blackspot bruises develop within a 24-hour period, with most bruises displaying discoloration within the first few hours after impact. This rapid development indicates that samples from handling operations could be evaluated sooner, shortening the standard evaluation period for blackspot bruise management. Previous practices used tetrazolium chloride or catechol solutions as methods to speed up the process of examining peeled tubers for bruise detection (Beaver and DeVoy 1986; Thornton et al. 1973) or ‘hot boxes’ to accelerate bruise development at warmer temperatures (McRae and Melrose 1993; Wouters et al 1986; Dwelle and Stallknecht 1976). Our study concluded discoloration can be seen without the addition of solutions or drastically warm temperatures within the first few hours after impact when held at room temperature and even when held at typical storage temperatures. Overall, the highest incidence of blackspot bruise occurred at the last evaluation time; however, 70% of blackspot bruises were visible at hour four after impact. Pink discoloration peaked within the first two hours after impact, and then impacted areas rapidly began turning brown or black in color. Likewise, over 85% of shatter bruise incidence was visible by hour four after impact. From this data, blackspot and shatter bruise could be evaluated in four to five hours after a sample is taken if placed at room temperature (21°C). Although, development can be dependent on the severity of the bruise. Mild bruises will develop at a slower rate than more severe bruises as observed in the multiple experiments in this study. The development will not be complete between four to five hours, but many of the bruises will be visible and easily identifiable as pink, brown, or black discoloration.

To aide in adjusting equipment quickly during harvest and handling operations, tubers can be sampled for estimated bruise levels earlier than the previously recommended 24 hours or USDA-required 48 hours. This new data would allow for more rapid assessment during harvesting operations than the previously suggested 24-to-48-hour window, potentially saving millions of pounds of potatoes exposed to impact damage. For example, assume within 24-hour day potatoes are being harvested at the same volume per hour. For this example, imperial units are used to align with industry units. If samples are evaluated at hour four and high bruise levels detected, 84% of the remaining crop in that 24-hour window will have yet to be harvested. A four-row harvester (typical of machinery used in Idaho) going three mph equates to a harvesting capacity of 4.2 acres/hour, which is comparable to the 2.1 acres reported for a two-row harvester in Brazil (Cunha et al. 2011). A modern harvesting operation in Idaho uses multiple pieces of harvesting equipment and often harvest between 8 and 16 rows at one given time or between 8.4 and 16.8 acres per hour. This equates to 200 to 400 acres per 24-hour period. The average yield in Idaho for 2019 was 42,500 pounds per acre (USDA 2020b). Using a four-hour bruise evaluation window and assuming making proper mechanical adjustments to equipment would reduce exposure to bruise damage, then the quality of 7 to 14 million pounds of potatoes could be improved in the remaining 24-hour harvest period.

This study provided information to help establish cultivar-specific sampling methods for assessing bruise in a commercial operation. For R. Burbank, over 50% of the developing blackspot bruises were visible by hour two as a pink discoloration at the higher impact height. For the lower impact height, the majority of incidence occurred between hour three and five. Shatter bruise was visible and consistent one hour after impact for R. Burbank. To use a rapid bruise assessment for R. Burbank, place samples at room temperature and evaluate tubers for bruise between two to five hours to assess mild and severe bruises. Examining bruise development in R. Norkotah identified between hour two and three 51 to 57% of the total blackspot bruises from the higher impact height were visible. This cultivar can be assessed as early as two hours to see most of the blackspot bruises that will develop for major impacts. Ranger R. developed mild and severe bruises at the same rate and over 50% of the developing blackspot bruises were visible one hour after impact. Ranger R. is a promising candidate for rapid bruise assessment method due to the cultivar’s extremely rapid bruise development. To utilize this early bruise detection method, personnel would need to have the ability to see various colors associated with the development of blackspot bruises.

As potatoes are handled throughout post-harvest operations, they must adhere to established quality standards. USDA inspection guidelines for both the fresh and processing markets categorize a fresh bruise as having a “shade of pink or a bright shiny gray to jet black color and no sign of dry or dry starchy flesh” and an old bruise as “dull gray or light brown and other colors which show a dry or starchy appearance in the flesh” (USDA 2012-p. 21; USDA 2015-p. 42-43). For the fresh market, all bruises—no matter if they are fresh or old—will be scored as a defect (USDA 2012). For the processing market, scoring bruise becomes more complicated and heavily reliant on specifications from grower-supplier contracts (USDA 2020). USDA processing standards will score fresh bruises if potatoes are coming directly from the field. If coming out of storage only old bruises are scored (USDA 2015). For samples going into storage, potatoes must be held at least 48 hours prior to inspecting for bruise unless otherwise specified in contracts (USDA 2015). This study found that damaged areas on tubers can be a brown color within five hours after impact. This information about fresh, brown-colored bruises could aid in updating definitions within the USDA inspection guidelines. It also indicates that distinguishing between new and old bruises before and after holding for 48 hours can be difficult.

Most of the total depth of the bruise (70%) was developed by hour five after impact. Knowing more than half of the bruise depth is developed by hour five can help estimate quality for inspection purposes. Inspection procedures specify sampling a minimum of five potatoes to be cut for internal defects (USDA 2012, USDA 2015). A thin exploratory cut is made on the stem end of a tuber to inspect for blackspot bruise and other internal defects. If any internal defects are found, a minimum of an additional 20 pounds must be cut for internal grading (USDA 2012; USDA 2015). More severe bruises will extend deeper into the tissue, which will lead to additional investigation of quality concerns. Commercial operations can estimate how severe bruising may be if new bruises are extending deep into the tissue.

Previous research found warmer holding temperatures can accelerate the blackspot bruise development process (Thornton 1982; Burton 1989), but this study also examined how bruises developed at a typical storage temperature (8.9°C). At hour five after impact, 75% of blackspot bruises from the larger impacts (higher drop heights) were visible. This is roughly only one hour later in development compared to the warmer holding temperature of 21°C. Differences in bruise development could also be seen between the bud and stem end of the tuber at these lower storage temperatures. The bud end remained at a similar developmental phase of discoloration and depth until hour three for major impacts and hour five for minor impacts. After hour three or five, discoloration and depth increased substantially by hour 24. For minor impacts, discoloration and depth remained the same between hour 24 and 48, although there was a slight increase in major impacts. Shatter bruise was visible one hour after impact and development stayed similar at the 8.9°C storage temperature throughout the rest of timeframe examined. Dwelle and Stallknecht (1976) held tubers at 10°C and saw slower blackspot bruise development compared to development at 40°C stating that maximum melanin formation was seen after 48 hours. This study added the finding that storage temperatures only slow the development of blackspot bruise by a few hours and did not alter shatter bruise development. Implications from this study address the potential for new bruises to form at lower tuber pulp temperatures within just a few hours after unloading from a storage.

Bruise development between tuber ends was different throughout all the experiments examined of this study. The bud end had lower overall blackspot bruise incidence, severity and depth and was slower to develop blackspot bruise than the stem end. Previous research found differing concentrations of biochemical compounds between the bud and the stem end (Lui et al. 2016; Reeve et al. 1969), which may explain why development is slower on the bud end. An example of this difference can be seen with tyrosine concentrations. Tyrosine has been reported to be 20 to 40% more concentrated in the stem end of the tuber as compared to the bud end (Reeve et al. 1969; Rastovski and Es 1981). Since tyrosine is a key component in melanin formation, the data showing rapid and greater blackspot bruise development on the stem end corresponds well to the literature. The difference in shatter bruise response between tuber ends may be due to the unique cellular structure of the tuber. During plant growth, tuberization occurs at the stolon tip and includes rapid cell division and expansion (Xu et al. 1998). In the stem region (where the newest tissue is forming) the cells first enlarge then divide longitudinally, whereas in the bud region the cells divide transversally and then elongate (Xu et al. 1998). The way these cells divide during growth dictate how cell structure develops. Cellular structure may determine why cell walls break (shatter bruise) under impact stress.

Conclusion

This study implies there are potential savings for the industry in terms of time, money, crop loss, and resources by utilizing rapid bruise assessment techniques to aid in adapting bruise management programs. The methodology used in this study provided reliable results for bruise development across multiple cultivars and impact heights. The majority of bruise developed within the first four hours after impact and that time can be utilized as an adequate timeframe to estimate bruise levels in harvest and handling operations. This study highlights the effectiveness of utilizing fresh, developing bruises as means to indicate the need to make quicker modifications to equipment than the previously recommended 24-hour timeframe and subsequently evolve bruise management in the potato industry. Future research should determine why there are major differences in bruise development between tuber ends and examine development when tubers are impacted at different pulp temperatures to help further define cultivar-specific rapid bruise assessment recommendations.

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Tables

Table 3-1. List of experiments, objectives and trial dates conducted to examine blackspot and shatter bruise development.

#	Experiment	Objective goal[1]	Trial Dates
	Meta-analysis[2]	Bruise development in a 24-hour period	
Russet Burbank bruise development at 21.1°C			
1	18 cm	Bruise development, impact height	Dec. 19, 2018; Feb. 12, 2019; Oct. 23, 2019; May 18, 2020
2	30 cm	Bruise development, cultivar, impact height	Dec. 13, 2018; Feb 19, 2019; Oct. 23, 2019; May 18, 2020
Russet Norkotah bruise development at 21.1°C			
3	30 cm	Bruise development, cultivar	Feb. 22, 2019; Mar. 7, 2019; Oct. 23, 2019; May 18, 2020
Ranger Russet bruise development at 21.1°C			
4	18 & 30 cm	Bruise development, cultivar, impact height	Oct. 29, 2019; May 18, 2020
Russet Burbank bruise development at 8.9°C			
5	18 cm	Bruise development, development temperature	Feb. 13, 2020; May 13, 2020
6	30 cm	Bruise development, development temperature	Mar. 19, 2019; Mar. 26, 2019; Feb. 13, 2020; May 13, 2020

[1] There were four main objectives for this study. Bruise development denotes the first objective: how bruise developed hourly in the first five hours after impact compared to 24 or 48 hours after impact. Cultivar denotes the second objective: how quickly each cultivar developed bruises. Impact force denotes the third objective: observe if impact force could influence how quickly bruises develop. Development temperature denotes objective four: understand how quickly bruise developed at storage temperatures.

[2] Meta-analysis was a compilation of experiments 1-6 examining bruise development in a 24-hour period. Experiment, cultivar, impact height, and evaluation temperature were added as random variables in each linear model for blackspot bruise incidence, color intensity, depth, and shatter bruise incidence. Hours after impact and tuber end were designated as main effects in the models.

Table 3-2. Meta-analysis main effects on bruise development in a 24-hour period after impact and between tuber ends. Meta-analysis included Russet Burbank bruise development at 21.1°C and 8.9°C for 18 and 30 cm, Russet Norkotah bruise development at 21.1°C for 30 cm, and Ranger Russet bruise development at 21.1°C for 18 and 30 cm where experiment, cultivar, impact height, and evaluation temperature were added as random variables to each linear model.

	Blackspot bruise Incidence (%)[1]	Blackspot bruise color intensity rating (1-5)[2]	Blackspot bruise depth (mm)	Shatter bruise incidence (%)
Hours after impact				
1	31 a	1.3 a	1.4 a	15 a
2	42 b	1.5 b	2.0 b	15 a
3	51 c	1.7 c	2.6 c	15 a
4	57 d	2.1 d	3.0 d	18 b
5	60 d	2.3 e	3.3 e	18 b
24	81 e	3.7 f	4.7 f	21 c
P-value	<0.0001	<0.0001	<0.0001	<0.0001
Tuber end				
Bud	38 a	1.7 a	2.0 a	21 b
Stem	69 b	2.5 b	3.7 b	13 a
P-value	<0.0001	<0.0001	<0.0001	<0.0001

[1] Values followed by the same letter are not significantly different (α<0.05) for each variable within each column.

[2] Blackspot bruise color intensity scale of 1 to 5: 1= none, 2=pink, 3=light brown, 4=dark brown, to 5=black discoloration.

Table 3-3. Blackspot bruise incidence, color intensity rating, blackspot bruise depth and shatter bruise incidence between hours after impact and tuber ends for Russet Burbank impacted at an 18 cm drop height and bruise evaluation at 21.1°C.

	Blackspot bruise Incidence (%)[1]	Blackspot bruise color intensity rating (1-5)[2]	Blackspot bruise depth (mm)	Shatter bruise incidence (%)
Hours after impact				
1	22 a	1.2 a	0.9 a	6
2	34 b	1.4 a	1.7 b	9
3	45 c	1.6 b	2.2 c	6
4	48 c	1.8 c	2.4 cd	10
5	52 c	2.1 d	2.7 d	7
24	72 d	3.3 e	3.9 e	10
P-value	<0.0001	<0.0001	<0.0001	0.10
Tuber end				
Bud	29 a	1.5 a	1.4 a	12 b
Stem	62 b	2.3 b	3.2 b	4 a
P-value	<0.0001	<0.0001	<0.0001	<0.0001

[1] Values followed by the same letter are not significantly different ($\alpha<0.05$) for each variable within each column.

[2] Blackspot bruise color intensity scale of 1 to 5: 1= none, 2=pink, 3=light brown, 4=dark brown, to 5=black discoloration.

Table 3-4. Blackspot bruise incidence, color intensity rating, blackspot bruise depth and shatter bruise incidence between hours after impact and tuber ends for Russet Burbank impacted at a 30 cm drop height and bruise evaluation at 21.1°C.

	Blackspot bruise Incidence (%)[1]	Blackspot bruise color intensity rating (1-5)[2]	Blackspot bruise depth (mm)	Shatter bruise incidence (%)
Hours after impact				
1	44 a	1.5 a	1.9 a	28
2	56 b	1.6 a	2.8 b	22
3	66 c	2.0 b	3.5 c	22
4	70 c	2.5 c	4.3 d	29
5	73 c	2.8 d	4.6 d	27
24	96 d	4.3 e	5.8 e	23
P-value	<0.0001	<0.0001	<0.0001	0.13
Tuber end				
Bud	56 a	2.1 a	3.1 a	35 b
Stem	79 b	2.8 b	4.5 b	15 a
P-value	<0.0001	<0.0001	<0.0001	<0.0001

[1] Values followed by the same letter are not significantly different ($\alpha<0.05$) for each variable within each column.

[2] Blackspot bruise color intensity scale of 1 to 5: 1= none, 2=pink, 3=light brown, 4=dark brown, to 5=black discoloration.

Table 3-5. Blackspot bruise incidence, color intensity rating, blackspot bruise depth and shatter bruise incidence between hours after impact and tuber ends for Russet Norkotah impacted at a 30 cm drop height and bruise evaluation at 21.1°C.

	Blackspot bruise Incidence (%)[1]		Blackspot bruise color intensity rating (1-5)[2]		Blackspot bruise depth (mm)		Shatter bruise incidence (%)	
Hours after impact								
1	23	a	1.2	a	1.0	a	12	a
2	43	b	1.5	b	1.9	b	13	ab
3	48	b	1.7	c	2.2	c	12	ab
4	59	c	2.2	d	2.8	d	16	bc
5	60	c	2.4	e	3.0	d	11	a
24	84	d	3.9	f	4.5	e	18	c
P-value	<0.0001		<0.0001		<0.0001		0.01	
Tuber end								
Bud	34	a	1.7	a	1.6	a	12	a
Stem	72	b	2.6	b	3.6	b	15	b
P-value	<0.0001		<0.0001		<0.0001		0.006	

[1] Values followed by the same letter are not significantly different (α<0.05) for each variable within each column.

[2] Blackspot bruise color intensity scale of 1 to 5: 1= none, 2=pink, 3=light brown, 4=dark brown, to 5=black discoloration.

Table 3-6. Blackspot bruise incidence, color intensity rating, blackspot bruise depth and shatter bruise incidence between hours after impact, impact height, tuber ends, and time in storage for Ranger Russet bruise development at 21.1°C.

	Blackspot bruise Incidence (%)[1]	Blackspot bruise color intensity rating (1-5)[2]	Blackspot bruise depth (mm)	Shatter bruise incidence (%)
Hours after impact				
1	50 a	1.6 a	2.1 a	8
2	53 a	1.8 b	2.4 b	6
3	69 b	2.4 c	3.4 c	9
4	72 b	3.0 d	3.4 c	8
5	70 b	3.1 d	3.5 c	8
24	89 c	4.0 e	5.1 d	8
P-value	<0.0001	<0.0001	<0.0001	0.71
Impact height (cm)				
18	61 a	2.5 a	2.8 a	5 a
30	73 b	2.8 b	3.8 b	10 b
P-value	<0.0001	<0.0001	<0.0001	<0.0001
Tuber end				
Bud	45 a	1.9 a	2.0 a	15 b
Stem	89 b	3.3 b	4.6 b	1 a
P-value	<0.0001	<0.0001	<0.0001	<0.0001

[1] Values followed by the same letter are not significantly different (α<0.05) for each variable within each column.

[2] Blackspot bruise color intensity scale of 1 to 5: 1= none, 2=pink, 3=light brown, 4=dark brown, to 5=black discoloration.

Table 3-7. Blackspot bruise incidence, color intensity rating, blackspot bruise depth and shatter bruise incidence between hours after impact and tuber ends for Russet Burbank impacted with an 18 cm drop height and stored at 8.9°C.

	Blackspot bruise Incidence (%)[1]	Blackspot bruise color intensity rating (1-5)[2]	Blackspot bruise depth (mm)	Shatter bruise incidence (%)
Hours after impact				
1	10 a	1.1 a	0.4 a	5
2	15 a	1.2 a	0.6 a	4
3	18 a	1.2 ab	0.8 a	2
4	26 b	1.4 bc	1.2 b	4
5	32 b	1.5 c	1.6 b	6
24	60 c	3.0 d	3.0 c	3
48	68 d	3.5 e	3.7 d	4
P-value	<0.0001	<0.0001	<0.0001	0.24
Tuber end				
Bud	20 a	1.5 a	0.9 s	7 b
Stem	46 b	2.2 b	2.3 b	1 a
P-value	<0.0001	<0.0001	<0.0001	<0.0001

[1] Values followed by the same letter are not significantly different ($\alpha<0.05$) for each variable within each column.

[2] Blackspot bruise color intensity scale of 1 to 5: 1= none, 2=pink, 3=light brown, 4=dark brown, to 5=black discoloration.

Table 3-8. Blackspot bruise incidence, color intensity rating, blackspot bruise depth and shatter bruise incidence between hours after impact and tuber ends for Russet Burbank impacted with a 30 cm drop height and bruise evaluation at 8.9°C.

	Blackspot bruise Incidence (%)[1]	Blackspot bruise color intensity rating (1-5)[2]	Blackspot bruise depth (mm)	Shatter bruise incidence (%)
Hours after impact				
1	39 a	1.4 a	2.0 a	31 b
2	50 b	1.5 ab	2.6 b	29 b
3	55 b	1.6 b	2.9 b	24 a
4	64 c	1.9 c	3.5 c	29 b
5	69 c	2.1 d	3.9 d	32 b
24	88 d	3.9 e	5.7 e	31 b
48	92 d	4.3 f	6.5 f	30 b
P-value	<0.0001	<0.0001	<0.0001	0.005
Tuber end				
Bud	56 a	2.1 a	3.4 a	36 b
Stem	74 b	2.6 b	4.4 b	22 a
P-value	<0.0001	<0.0001	<0.0001	<0.0001

[1] Values followed by the same letter are not significantly different ($\alpha<0.05$) for each variable within each column.

[2] Blackspot bruise color intensity scale of 1 to 5: 1= none, 2=pink, 3=light brown, 4=dark brown, to 5=black discoloration.

Figures

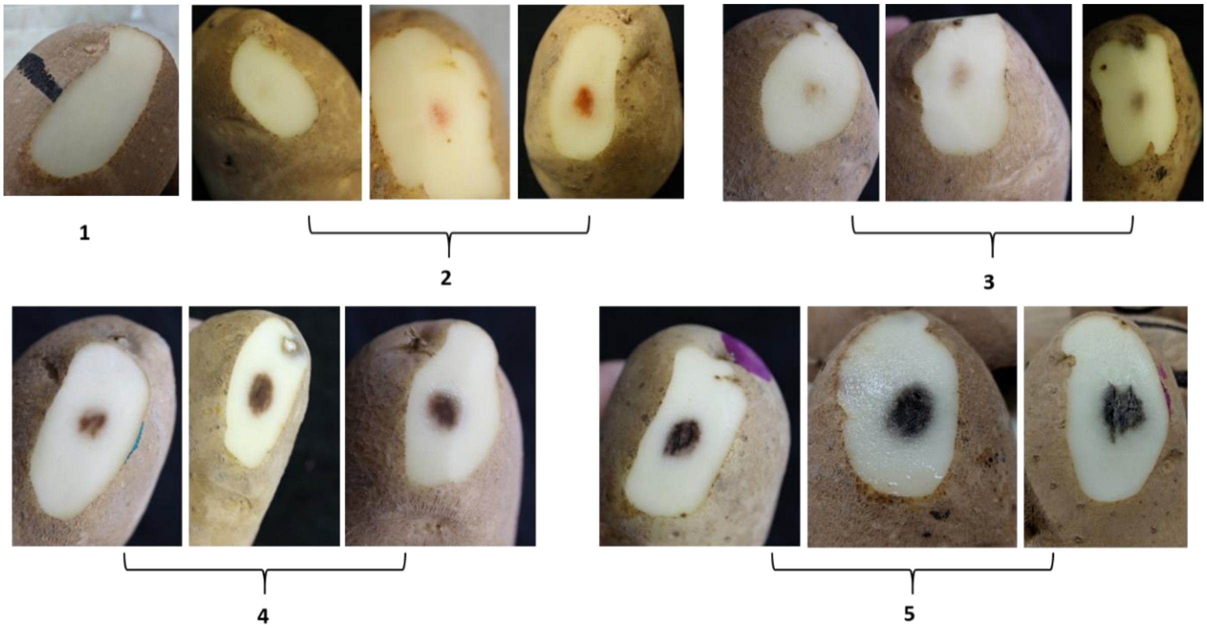

Figure 3-1. Blackspot bruise color intensity scale of 1 to 5: 1= none, 2=pink, 3=light brown, 4=dark brown, to 5=black discoloration.

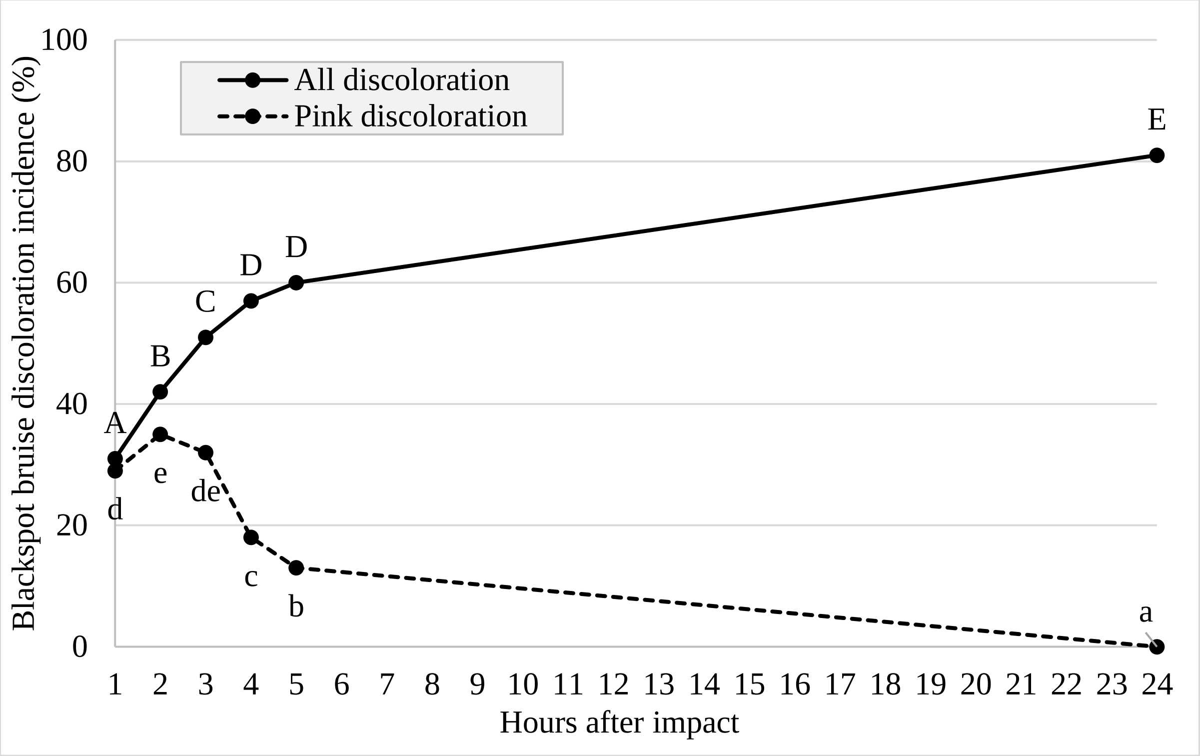

Figure 3-2. Blackspot bruise discoloration development within 24 hours. Values followed by the same letter are not significantly different (α<0.05) for all discoloration (uppercase) and pink discoloration (lowercase).

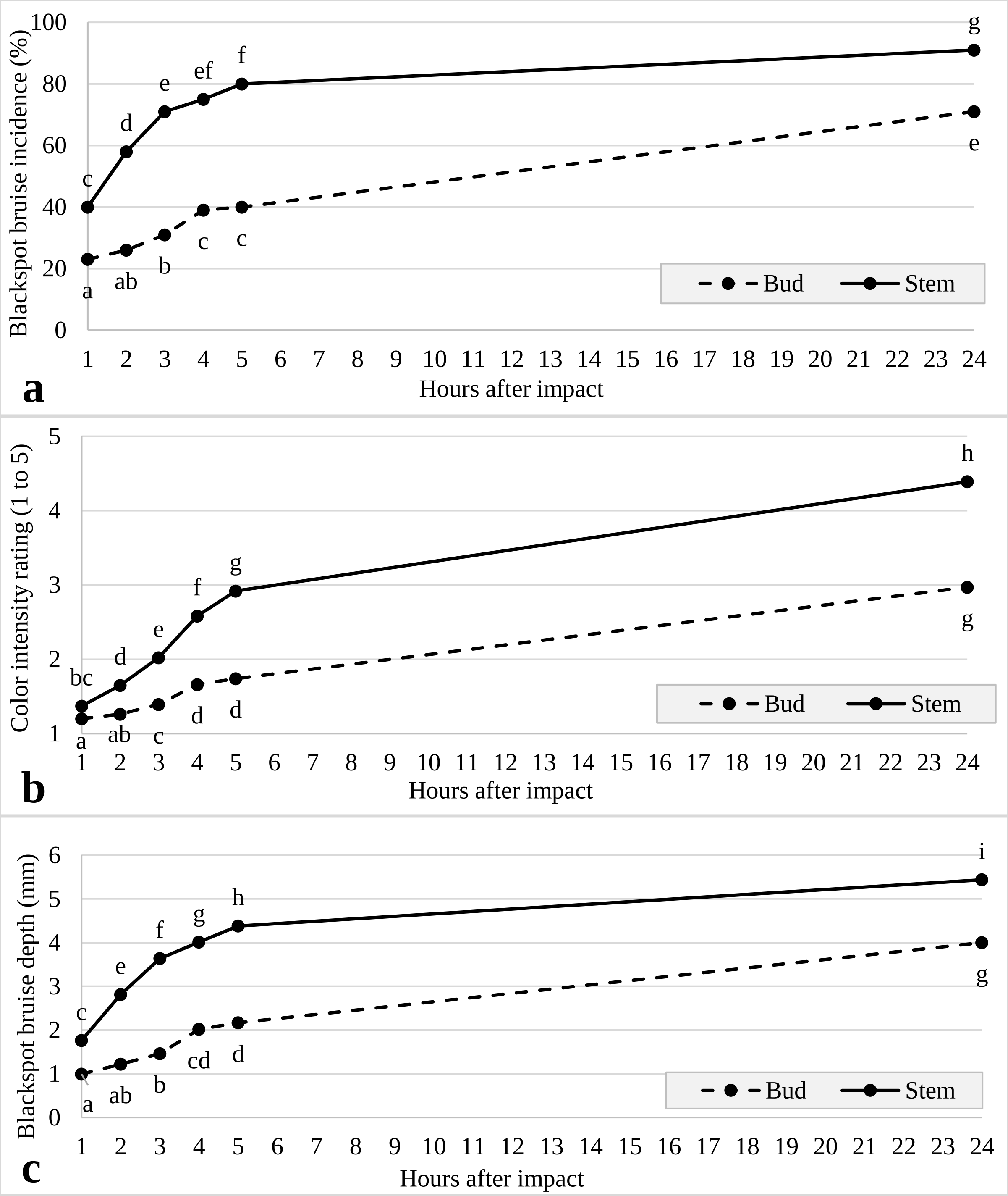

Figure 3-3. Meta-analysis interaction between tuber ends and hours after impact for a) blackspot bruise incidence, b) bruise color intensity, and c) bruise depth. Values followed by the same letter are not significantly different (α<0.05) for each graph.

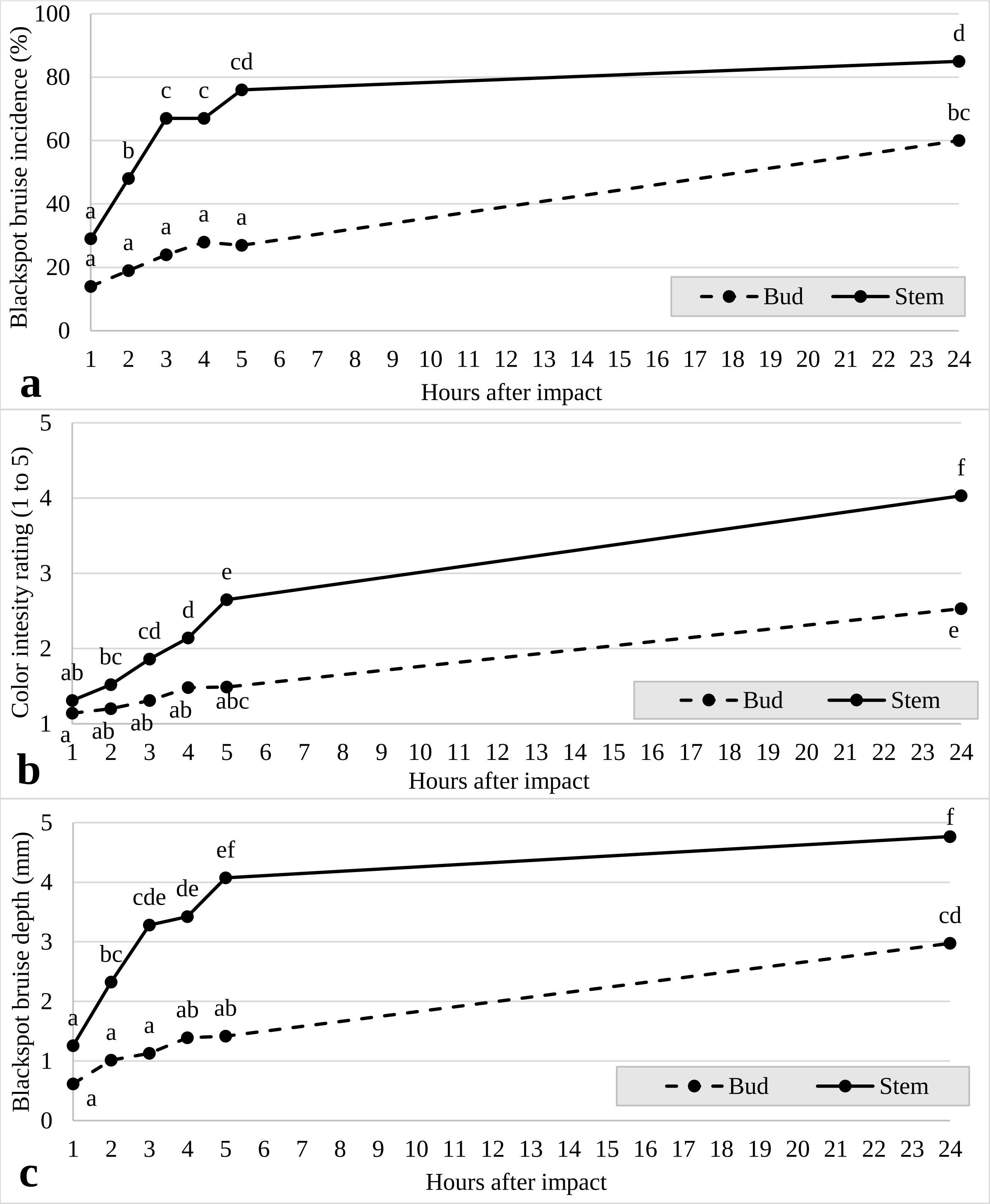

Figure 3-4. Interaction between tuber ends and hours after impact for a) blackspot bruise incidence, b) bruise color intensity, and c) bruise depth for Russet Burbank impacted at an 18 cm drop height and bruise evaluation at 21.1°C. Values followed by the same letter are not significantly different (α<0.05) for each graph.

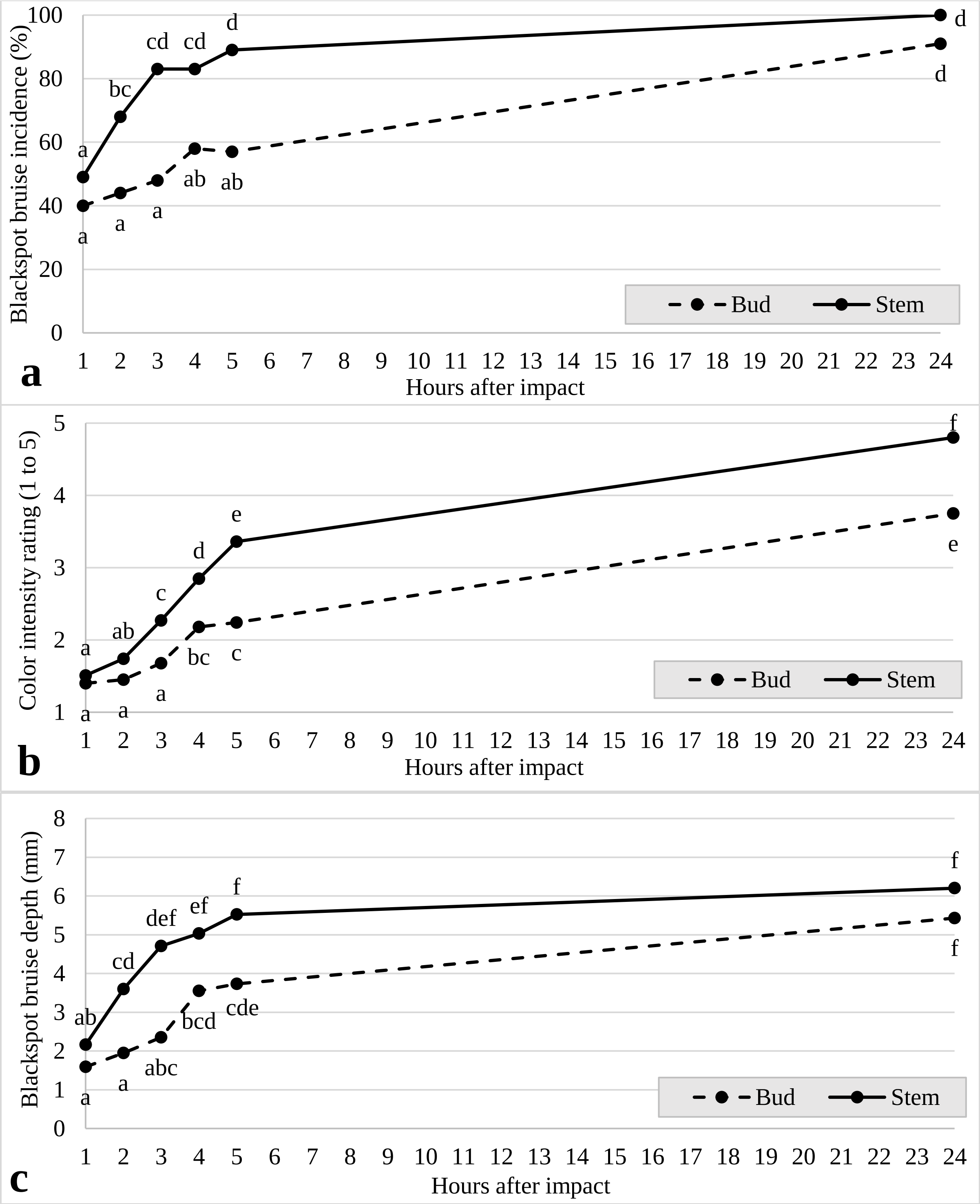

Figure 3-5. Interaction between tuber ends and hours after impact for a) blackspot bruise incidence, b) bruise color intensity, and c) bruise depth for Russet Burbank impacted at a 30 cm drop height and bruise evaluation at 21.1°C. Values followed by the same letter are not significantly different ($\alpha<0.05$) for each graph.

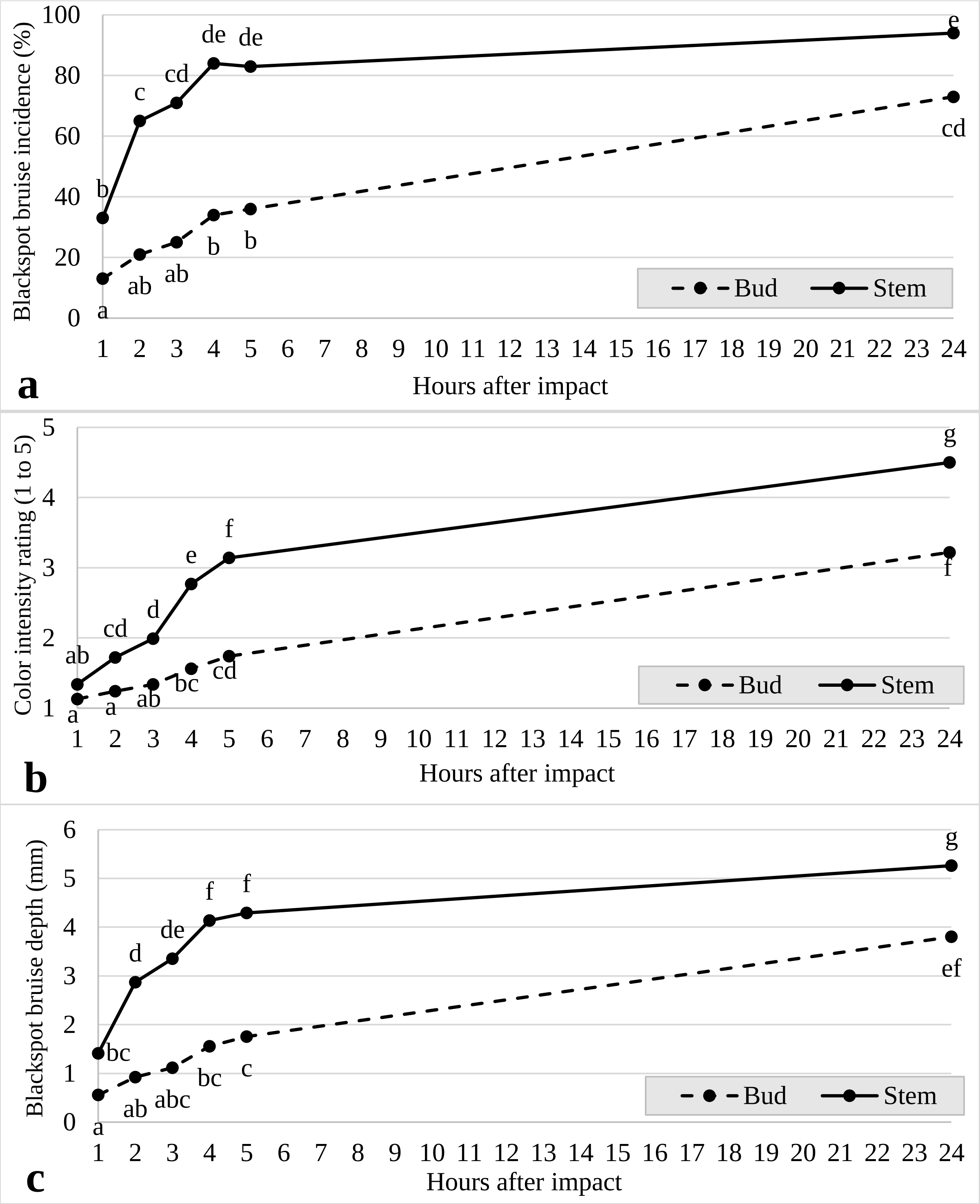

Figure 3-6. Interaction between tuber ends and hours after impact for a) blackspot bruise incidence, b) bruise color intensity, and c) bruise depth for Russet Norkotah impacted at a 30 cm drop height and bruise evaluation at 21.1°C. Values followed by the same letter are not significantly different (α<0.05) for each graph.

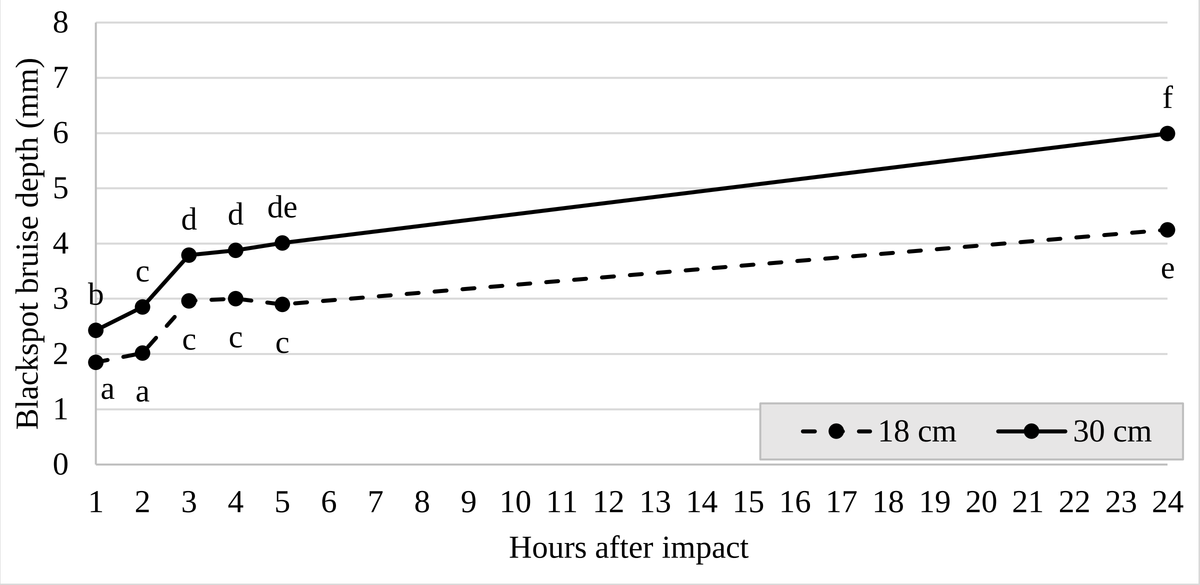

Figure 3-7. Blackspot bruise depth (mm) hourly development for Ranger Russet at 18 and 30 cm impact heights. Results are averaged over tuber end and time in storage. Values followed by the same letter are not significantly different (α<0.05).

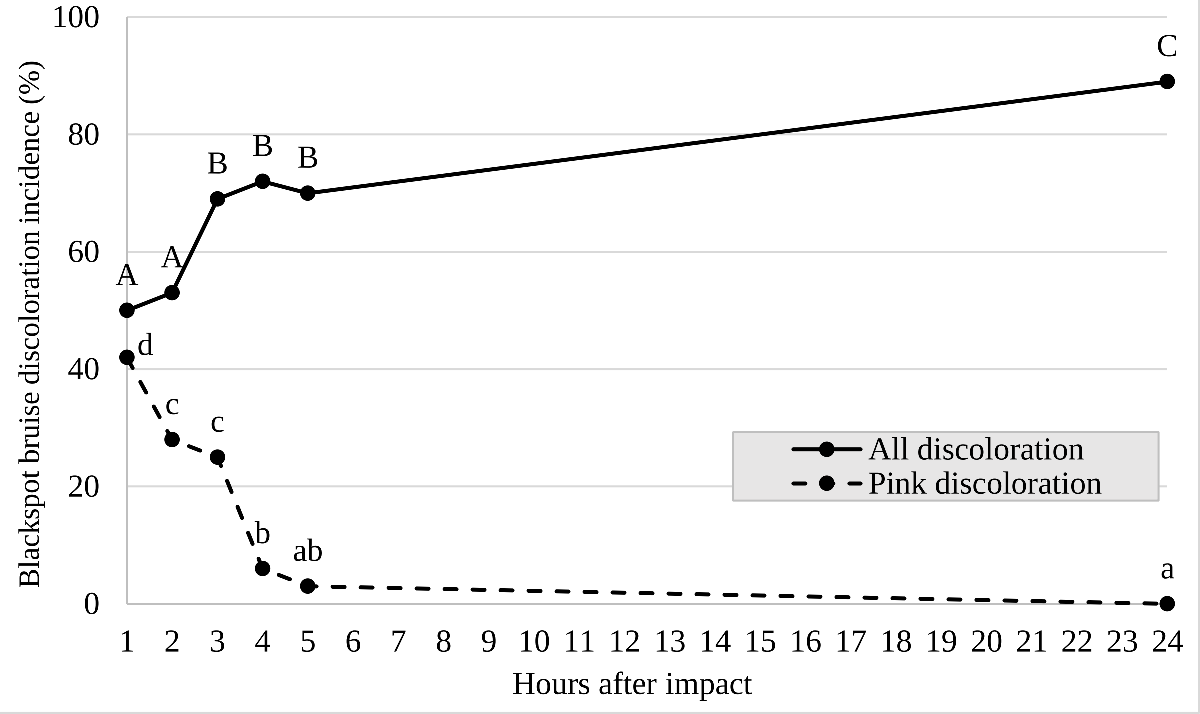

Figure 3-8. Blackspot bruise discoloration for Ranger Russet. Results are averaged over impact height, tuber end, and time in storage. Values followed by the same letter are not significantly different (α<0.05) for all discoloration (uppercase) and pink discoloration (lowercase) for each graph.

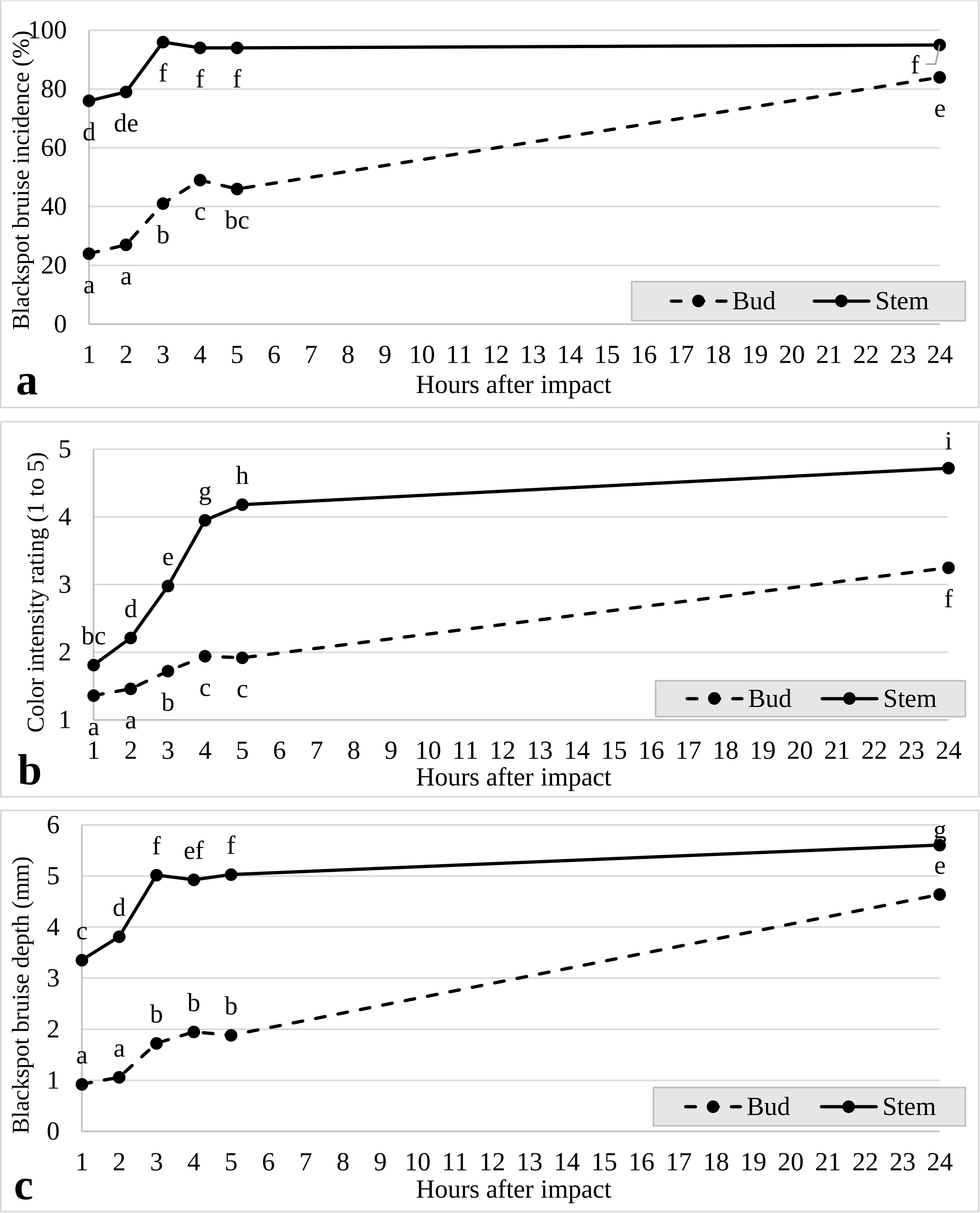

Figure 3-9. Interaction between tuber ends and hours after impact for a) blackspot bruise incidence, b) bruise color intensity, and c) bruise depth for Ranger Russet. Results averaged over impact height and time in storage. Values followed by the same letter are not significantly different (α<0.05) for each graph.

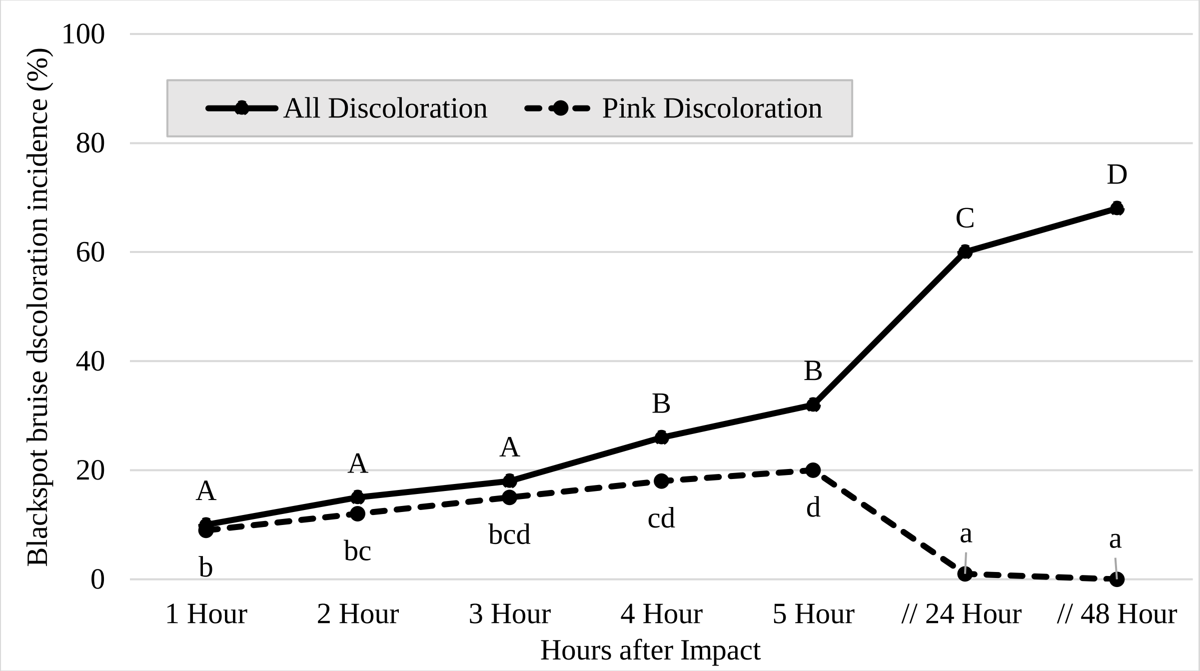

Figure 3-10. Blackspot bruise discoloration for Russet Burbank for 18 cm impact and evaluation temperature of 8.9°C. Values followed by the same letter are not significantly different (α<0.05) for all discoloration (uppercase) and pink discoloration (lowercase) for each graph.

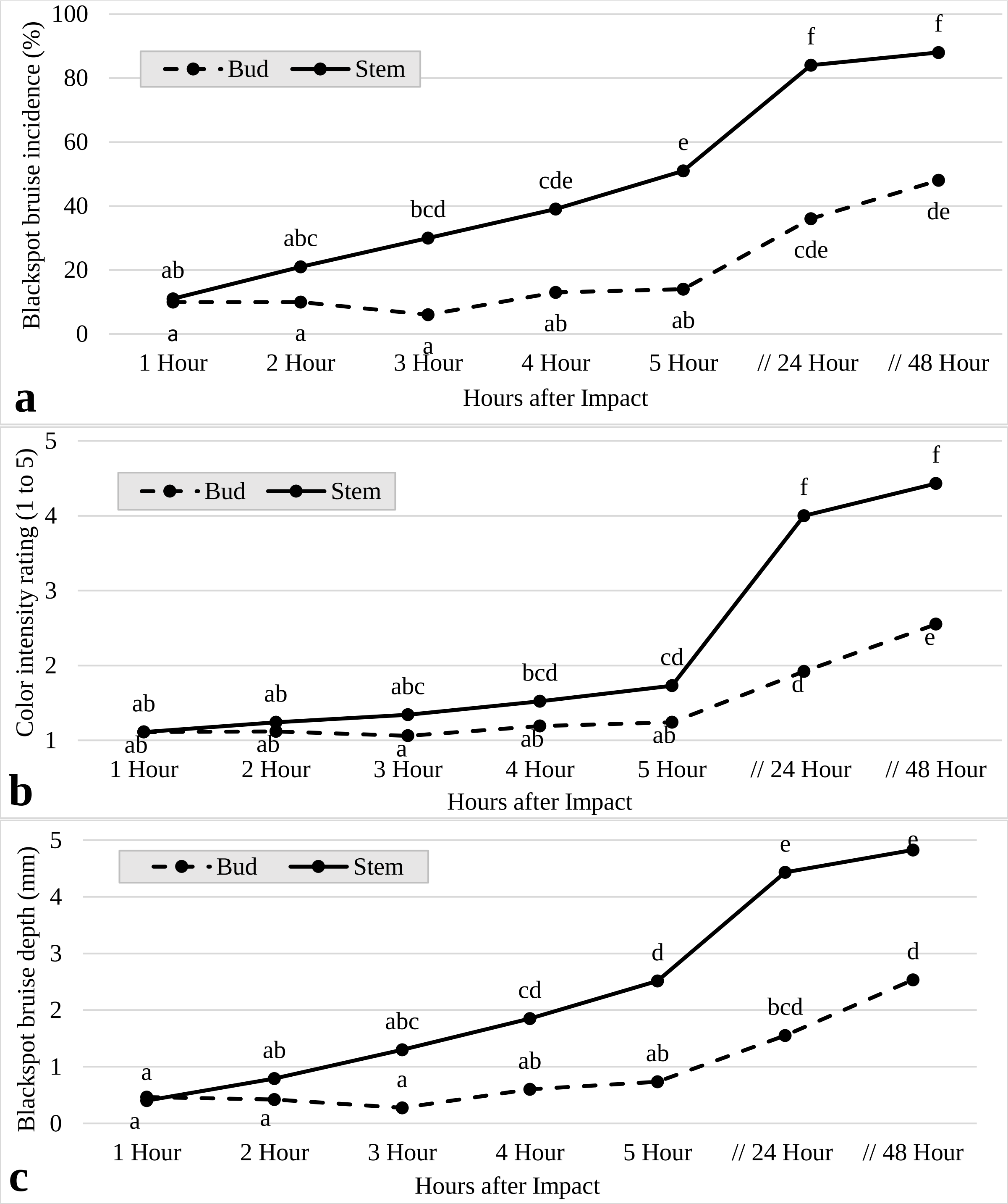

Figure 3-11. Interaction between tuber end and hours after impact for a) blackspot bruise incidence, b) bruise color intensity, and c) bruise depth for Russet Burbank impacted at 18 cm and evaluated at 8.9°C. Values followed by the same letter are not significantly different (α<0.05) for each graph.

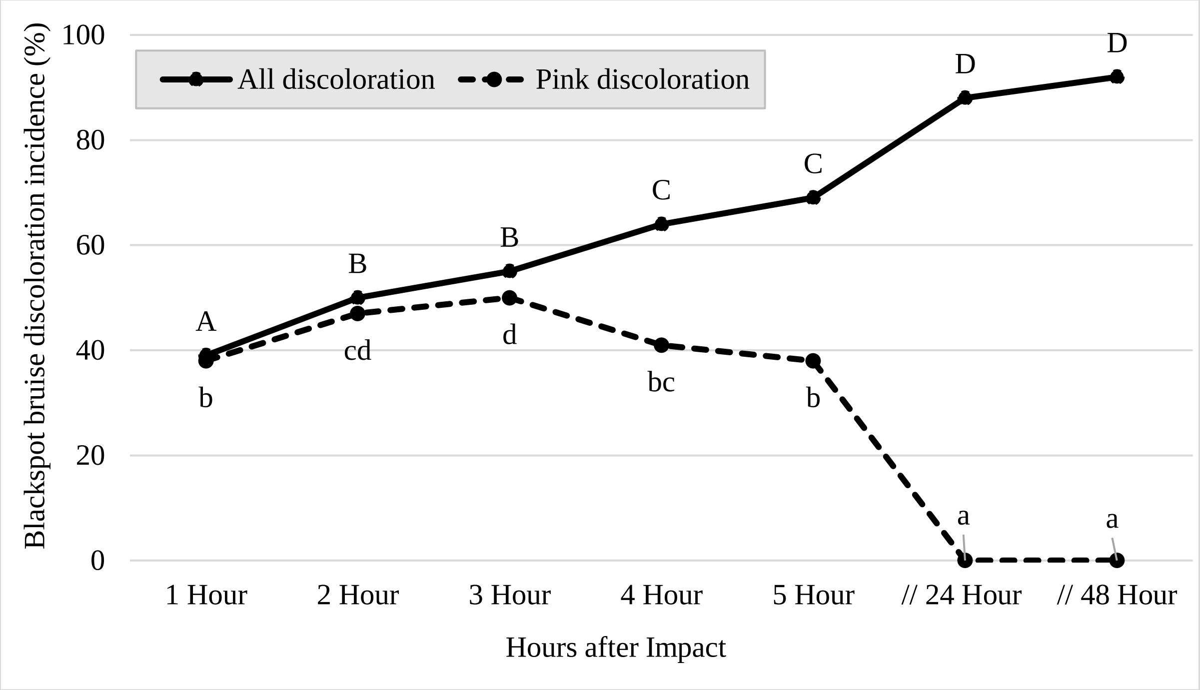

Figure 3-12. Blackspot bruise discoloration for Russet Burbank for 30 cm impact and evaluation temperature of 8.9°C. Values followed by the same letter are not significantly different (α<0.05) for all discoloration (uppercase) and pink discoloration (lowercase) for each graph.

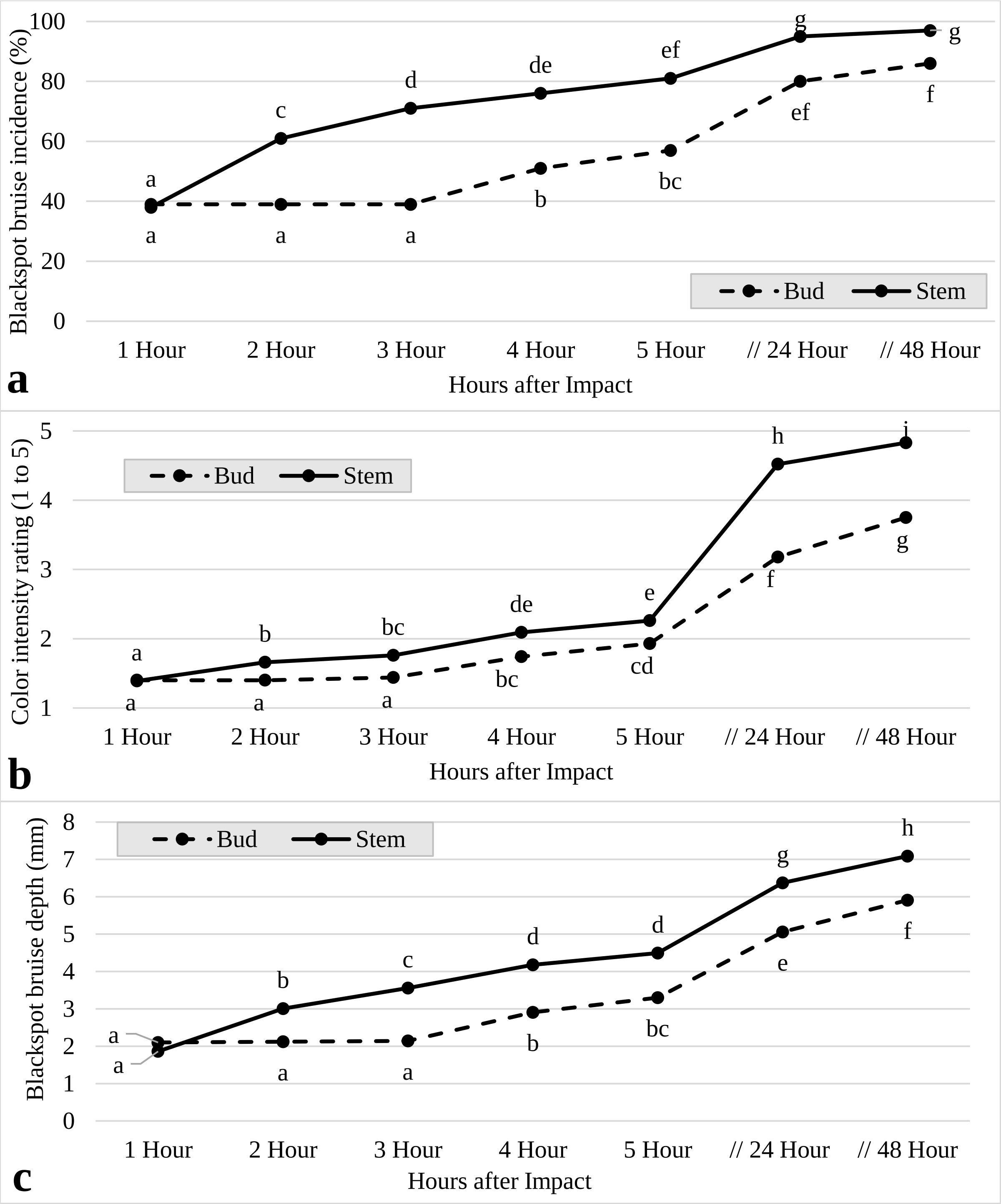

Figure 3-13. Interaction between tuber end and hours after impact for a) blackspot bruise incidence, b) bruise color intensity, and c) bruise depth for Russet Burbank impacted at 30 cm and evaluated at 8.9°C. Values followed by the same letter are not significantly different (α<0.05) for each graph.

Chapter 4: Susceptibility of Potato Cultivars to Blackspot and Shatter Bruise at Three Impact Heights

Abstract

Handling potatoes can create opportunities to develop bruise resulting in quality defects. Understanding cultivar specific bruise susceptibility can aid in developing appropriate bruise management programs. A trial was conducted to examine how bruise susceptibility in russet cultivars are affected by impact height. Six cultivars, Russet Burbank, Ranger Russet, Clearwater Russet, Dakota Russet, Teton Russet, and Umatilla Russet (R.=Russet) were impacted using a device, which dropped a 100 g steel weight from 8, 18, or 30 cm height, to deliver a uniform impact on both the bud and stem end of a stationary tuber (pulp temperature of 8.9°C). Blackspot bruise incidence, severity and depth and shatter bruise incidence were evaluated. Blackspot and shatter bruise were significantly influenced by impact height and tuber end in all cultivars examined. Clearwater R. and Dakota R. had the highest blackspot bruise incidence (88 to 89%, respectively) compared to other cultivars examined (67 to 81%). Teton R. had the lowest blackspot bruise incidence (67%), severity rating (2.0) and depth (3.7 mm) examined among the 6 cultivars but had the highest shatter bruise incidence observed (14%). Overall, the bud end had lower blackspot bruise incidence, severity and depth than the stem end for all cultivars, although the difference between ends was dependent on cultivar. As impact height increased, blackspot bruise incidence, severity, depth and shatter bruise incidence increased. There were no significant differences between cultivars in shatter bruise at the 8 cm impact height (1 to 2%), but differences between cultivars became evident at 18 cm impact height (2 to 11%) and 30 cm impact heights (6 to 33%). Shatter bruise incidence did not differ between tuber ends at the 8 cm impact height (1%), but the bud end showed increased incidence at 18 cm impact height (13%) and 30 cm impact height (34%) compared to the stem end (1 to 6%). An effective way to reduce bruise incidence for R. Burbank, Ranger R., Teton R., and Umatilla R. would be to lower the impact height or the impact force during handling operations. Clearwater R. and Dakota R. are more sensitive to blackspot bruise, so additional management practices such as monitoring for appropriate pulp temperatures during handling may be more critical to integrate into a cultivar specific bruise management program. This study provided insight on the importance of including more than one impact height to develop robust cultivar specific bruise susceptibility levels in research programs.

Introduction

There are multiple market uses for potatoes, but the primary uses in the United States are frozen potato products, fresh potatoes, and potato chips accounting for 87% of the United States potato production in 2019 (National, 2020). Potato quality is important for the grower, processor, and consumer to maximize efficiency and inputs, satisfy expectations, and to minimize food waste. One way the market ensures quality adherence is through quality assurance inspections and quality standards. Quality can be impacted by diseases, internal and external discoloration, and most notably, bruises. Bruise occurs when potatoes are damaged during harvest and handling operations and can be economically detrimental. In 1995, potato bruises were estimated to have caused the U.S. potato industry a loss of $298 million (Thornton and Bohl 1995). Reducing bruise one percentage was estimated to save growers $3 million annually in 1992 (Hyde et al. 1992); which computes to $5.6 million today factoring for inflation. Bruise management is critical to ensure a high-quality crop with minimal defects. Bruise-free percentages are calculated to further incentivize for quality in processed potato contracts (USDA 2015). Growers and processors utilize contracts to ensure the quality demands are upheld. Multiple russet cultivars are grown for the frozen processing market and one way to manage bruise for this market sector is by developing cultivar-specific bruise management recommendations.

Two major impact-related injuries are blackspot and shatter bruises. Blackspot bruising occurs when a tuber’s cell membranes are damaged, but the skin is unbroken. The intracellular membranes rupture causing a biochemical reaction to occur between polyphenol oxidase (PPO), tyrosine, and other substrates, resulting in melanin formation that appears as a dark discoloration at the area of impact (Edgell et al. 1998; Vreugdenhil et al. 2007; Dean 1996). Shatter bruises split the cell walls of the damaged area and expand outward and deep into the tissue. Shatter bruise can affect the skin quality, because it results in large cuts and visible splitting of the skin (Vreugdenhil et al. 2007; Hollingshead et al. 2020), as well as creating storability issues (McGarry et al. 1996) and entry points for pathogen infections (Singh et al. 2021).

One major adjustment that can be made during the harvest and handling process of the potato is to reduce the drop height as tubers transition from one surface to another. Lowering drop heights in a handling operation has been well-documented to lower bruise potential (Corsini et al. 1999; Mathew and Hyde 1997; Partington et al. 1999; Thornton and Bohl 1995; Xie et al. 2020). McGarry et al. (1996) indicated higher impact heights will result in shatter bruise, while lower impacts tend to cause blackspot bruise formation. Noble (1985) found long impact durations and low loading velocities will produce blackspot bruise whereas short impact durations and high loading velocities will produce more shatter bruise. Impact duration and loading velocities help explain how the potato responds to different impact forces. The more a potato absorbs the force from a fall (long impact duration and low loading velocities) the greater the chance blackspot bruise will occur rather than shatter bruise. The less absorption from a higher fall, the opposite occurs (short duration and high loading velocity), and shatter bruise develops. Although research has examined drop heights and variables associated with drop heights as contributing factors to bruise susceptibility, there is a gap in knowledge regarding how cultivars respond to varying impact heights. This information would aid in the ability to use impact-specific recommendations for individual cultivars.

Russet Burbank (R. Burbank) was released in 1902 and is still one of the most widely grown cultivars in North America (Bethke et al. 2014). It has been extensively researched as a comparison in the development of newer cultivars and considered intermediately (Corsini 1996) or moderately (Love et al. 1994) susceptible to blackspot bruising. Russet Burbank has a relatively high susceptibility to shatter bruise (Spear et al. 2017). Ranger Russet (Ranger R.) was released in 1991 and is known for being more susceptible to blackspot bruise than R. Burbank (Love et al. 1998) and considered moderately susceptible to shatter bruise (Thornton and Olsen 2016). Umatilla Russet (Umatilla R.), released in 1998, is slightly more susceptible than R. Burbank to both types of bruises (Mosley et al. 2000). Clearwater Russet (Clearwater R.), released in 2008, has similar shatter bruise susceptibility as R. Burbank and greater resistance to blackspot bruise (Novy et al. 2010). Teton Russet (Teton R.), released in 2011, is more susceptible to shatter bruise but less susceptible to blackspot than R. Burbank (Novy et al. 2014). Dakota Russet (Dakota R.), released in 2012, is a multi-purpose cultivar and does not have bruise susceptibility data published to date. Each cultivar can vary in response an impact, therefore having data accessible about susceptibility due to different impact forces can reinforce cultivar-specific management for mechanical damage.

Determining cultivar bruise susceptibility can be challenging because there are no standard techniques for establishing bruise susceptibility levels (Opara and Pathare 2014). Methods of evaluating for bruise include collecting sample tubers from harvesting operations (Misener et al. 1989; Canneyt et al. 2004), pouring tubers on to shaking tables (Laerke et al. 2002b), using falling impact/bolt devices (Corsini et al. 1999; Maas 1966; Thornton 1982; Stevens and Davelaar 1997; Kunkel et al. 1986; Laerke et al. 2002a), dropping tubers on to different surfaces (Bajema and Hyde 1998), or examining cellular compounds within potato tissues (Linn and Pitt 1986). Bajema and Hyde (1998) noted that a smaller mass being dropped on to a stationary tuber (falling impact device) will need more force to equate to the same impact as a tuber dropping on to a surface. Pavek et al. (1985) found a high correlation between impact tests and enzymatic discoloration and concluded an abrasive peeling could be used to screen for resistance to bruise instead of impact tests. An impact device is a consistent method to examine bruise susceptibility over multiple cultivars and varying environmental circumstances because it removes variability for the size and shape of tuber (Maas 1966; McGarry et al. 1996; Kunkel et al. 1986). Due to the diversity in techniques in determining cultivar susceptibility to bruise and the potential response due to impact height, direct assessments using one method may help identify bruise susceptibly of processing cultivars.

Many factors contribute to bruise susceptibility beyond impact method. The primary factors considered to alter bruise susceptibility are impact force (Schippers 1971; Thornton and Timm 1990), tuber pulp temperature (Thornton et al. 1973; Smittle et al. 1974; McGarry et al. 1996; Baritelle and Hyde 2001; Xie et al. 2020), and cultivar selection (Blahovec and Židová 2004; Kunkel et al. 1978; Horvath 1986). Additional factors contributing to greater bruise susceptibility include pre-harvest field conditions: over mature tubers at vine kill (Corsini et al. 1999) or delayed vine killing dates (Pavek et al. 1985), and wet soil conditions at harvest (Thornton and Timm 1990). Other factors include tuber characteristics: concentrations of metabolites like tyrosine, threonine, valine, serine, and glutamine (Steinfath et al. 2010), concentration of calcium, magnesium, nitrogen and/or potassium in the tuber (Naumann et al. 2020; Kunkel et al. 1978; Karlsson et al. 2006), turgor levels (Kunkel and Gardner 1965; Konstankiewicz and Zdunek 2001; Lin and Pitt 1986), small cell size (Gancarz 2016), weak cellular structure (Konstankiewicz and Zdunek 2001), larger tuber mass (Baritelle and Hyde 1999), and higher specific gravities (Corsini et al. 1999; Baritelle and Hyde 2003). Differences in bruise susceptibility can be found between tuber ends as well (Bajema et al. 1998; Reeve et al. 1969). These previous studies are just a sample among a plethora of research trying to explain tuber blackspot and shatter bruise susceptibility. The distinction between blackspot and shatter bruise susceptibility is not always distinguishable in the literature, so some of the research conclusions include information pertaining to one or both types of bruises.

The objective of this study is to provide insight on how cultivar bruise susceptibility changes depending upon the impact height and location on the tuber. It will also provide information on bruise susceptibility of six commonly grown processing cultivars in the United States while determining cultivar and impact height specific bruise management practices.

Methods and Materials

This study was conducted over the 2019 and 2020 crop years. Certified seed for cv. Clearwater R., Dakota R., Ranger R., R. Burbank, Teton R., and Umatilla R. were planted at University of Idaho Kimberly Research and Extension Center (KREC) on April 25, 2019 and April 21, 2020, flail-mowed on September 12, 2019 and September 8, 2020, and harvested on September 24, 2019 and September 22, 2020. Harvested tubers were cured at 12.8°C for two weeks and stored at 8.9°C with 95% relative humidity (RH) at the KREC storage facility until trials were conducted. Each storage season, tubers received a thermal application of the sprout inhibitor isopropyl (3-chlorophenyl) carbamate (chlorpropham; Aceto Agricultural Chemicals Corporation) at 22 ppm on November 26, 2019 and November 19, 2020. Blackspot bruise severity, depth and incidence, as well as shatter bruise incidence, were evaluated at three impact heights using potatoes harvested from the

2019 and 2020 crops. The study was repeated four times (October 2019, April 2020, October 2020, and April 2021).

Bruise impact device protocols

Washed potatoes (170 to 450 g) were marked on predetermined locations void of obvious defects. The marked spots allowed for ease of knowing the location of the impact during evaluations. Tubers were impacted using a device that dropped a 100 g steel weight from 8, 18, or 30 cm height to deliver a uniform impact on a stationary tuber. Tubers were impacted on two locations on the apical (bud) end and two locations on the stolon (stem) end of each tuber. Preliminary data showed no significant differences between the two impacts sites on each end of the tuber, therefore in 2020 only one spot on each end was impacted. A 20-tuber subset sample (4 replicates) of each cultivar was impacted at each of the three drop height treatments. Pulp temperatures of tubers were 8.9°C at the time of impact, and tubers were subsequently stored at 21.1°C for 24 hours prior to bruise evaluation.

Evaluation of bruise

Marked and impacted areas were peeled using a standard vegetable peeler (Kuhn Rikon Original Swiss Peeler, Switzerland) and evaluated for blackspot bruise severity, bruise depth, incidence of blackspot bruise, and incidence of shatter bruise. Blackspot bruise severity was rated on the darkest color observed on a scale from 1 to 4: 1= no color, 2=light gray color, not severe but discoloration occurred, 3=dark gray color, severity is moderate, dark but not extreme, 4=dark gray/black color, severity is extreme (Figure 4-1). Blackspot bruise depth was evaluated by recording the number of slices removed by the peeler until no bruise was present. Preliminary research determined the average thickness of each slice to be 1.27 mm. Blackspot bruise depth was therefore calculated as the number of peels * 1.27 mm. Presence of shatter bruise was determined if there was a fracture in the cell wall visible after the first layer (1.27 mm) of the periderm was removed. Incidence of blackspot and shatter bruise were calculated by the presence or absence of bruise and calculated as a percentage of the impacted areas showing a bruise.

Statistical Analysis

Blackspot bruise severity, bruise depth, blackspot bruise incidence and shatter bruise incidence were analyzed using the analysis of variance (ANOVA) procedures in R (RStudio, package car version 3.0-9, 2020; Fox and Weisberg 2019). A linear model was fitted where cultivar, impact height, and tuber end were considered fixed effects. Storage season and trial were considered random effects. All trials' significant differences between means for response variables were compared at alpha of 0.05 by estimated marginal means procedures (RStudio, package emmeans version 1.6.1, 2020; Lenth 2021). Correlations between blackspot bruise severity and bruise depth were computed using the Spearman rank correlation (RStudio, package PerformanceAnalytics version 2.0.4, 2020; Peterson and Carl 2020).

Results

All blackspot and shatter bruise variables were significant (*P*<0.0001) for cultivar, impact height, and tuber end (Table 4-1). Clearwater R. and Dakota R. had the highest blackspot bruise incidence and were not significantly different from each other (88 to 89%, respectively), although Dakota R. had significantly higher blackspot bruise severity rating (2.7) and deeper bruises (5.8 mm) compared to Clearwater R. (2.6 rating, 5.1 mm, respectively). Ranger R. and Umatilla R. had similar blackspot bruise incidence (81 to 79%, respectively), although Ranger R. had significantly higher severity (2.5 rating) and deeper (5.1 mm) bruises than Umatilla R. (2.4 rating, 4.5 mm, respectively). R. Burbank had significantly lower blackspot bruise incidence (72%) and severity (2.3 rating) than Umatilla R. (79%, 2.4 rating), but had similar depth (4.6 and 4.5 mm, respectively). Teton R. had the lowest blackspot bruise incidence (67%), severity rating (2.0) and depth (3.7 mm) between the six cultivars but had the highest observed shatter bruise incidence (14%; Table 4-1). R. Burbank, Clearwater R., Ranger R., and Umatilla R. had similar shatter bruise incidence (9 to 11%); whereas Dakota R. had significantly lower shatter bruise incidence (3%).

As impact height increased, all blackspot and shatter bruise variables increased (Table 4-1). The bud end of the tuber had significantly lower blackspot bruise incidence (68%), severity rating (2.0) and depth (4.0 mm) than the stem end of the tuber (91%, 2.8 rating, 5.6 mm, respectively), but the bud end had significantly higher shatter bruise incidence (16%) than the stem end (3%).

There was a significant (*P*<0.0001) interaction between cultivar and impact height for all variables examined indicating cultivars responded differently to the various impact heights (Figure 4-2). Among the cultivars, Teton R. had the greatest differentiation to increasing impact heights for blackspot (difference of 51%) and shatter bruise incidence (difference of 32%), whereas Dakota R. had the smallest differentiation for these variables (differences of 20% and 5%, respectively). Interestingly, for blackspot bruise severity, Dakota R. had the greatest differentiation among cultivars (difference of 1.5 rating) compared to Umatilla R. that had the least differentiation (difference of 1.2 rating). For blackspot bruise depth, R. Burbank had the greatest differentiation (difference of 4.3 mm) whereas Umatilla R. had the least differentiation between increasing impact heights (difference of 3.0 mm). Blackspot bruise incidence for Clearwater R. and Dakota R. at the 18 cm impact height (92 and 93%, respectively) were not significantly different than the other cultivars (91 to 95%) at the higher impact height (30 cm; Figure 4-2a). Ranger R. and Umatilla R. were similar in blackspot bruise incidence at all impact heights examined, although Ranger R. had greater blackspot bruise severity and depth at 18 and 30 cm than Umatilla R. (Figure 4-2). Blackspot bruise severity for Teton R. (2.0

rating) at the 18 cm impact height was comparable to Clearwater R. and Dakota R. at the lower 8 cm impact height (1.9 rating). Dakota R. had significantly the deepest blackspot bruise depth (7.5 mm) at the 30 cm impact height. At the 18 cm force, Dakota R. (5.1 mm) had similar bruise depth compared to Teton R. (5.7 mm) and Umatilla R. (5.9 mm) at the higher impact height (30 cm). There were no significant differences between cultivars in shatter bruise at the 8 cm impact height (1 to 2%), but differences between cultivars became evident at 18 cm impact height (2 to 11%) and 30 cm impact height (6 to 33%). R. Burbank, Clearwater R., and Ranger R. showed similar shatter bruise incidence at each impact height examined (Figure 4-2d). R. Burbank, Clearwater R., Ranger R., and Umatilla R. had similar shatter bruise incidence at 30 cm (20 to 22%) whereas Dakota R. had lower incidence (6%), and Teton R. had higher (33%) at the same impact height.

There was a significant (*P*<0.0001) interaction between cultivar and tuber end for all variables examined indicating tuber end responded differently between cultivars (Figure 4-3). Blackspot bruise incidence was similar on the stem end for Clearwater R., Dakota R., Ranger R., and Umatilla R. (92 to 96%). Clearwater R. and Dakota R. had similar blackspot bruise incidence on the bud end (82 to 83%) and these cultivars had significantly higher incidence than Ranger R. (71%) and Umatilla R. (62%) on the bud end. R. Burbank and Teton R. had similar blackspot bruise incidence on the bud end (54% and 57%, respectively), but on the stem end R. Burbank had higher blackspot bruise incidence (91%) than Teton R. (77%). Dakota R. and Ranger R. had the highest severity ratings on the stem end (3.0 and 2.9 rating, respectively), but Ranger R. had a lower rating (2.1) on the bud end than Dakota R. (2.4 rating). Severity on the stem end for Teton R. (2.3 rating) was comparable to the bud end for Clearwater R. (2.3 rating) and Dakota R. (2.4 rating). Clearwater R., Ranger R., and Umatilla R. had similar blackspot bruise depth on the stem end (5.5 to 5.8 mm) but showed greater variability between cultivars on the bud end (3.4 to 4.7 mm). Shatter bruise incidence on the stem end was 6% or lower for all cultivars. Teton R. and Umatilla R. had similar shatter bruise incidence on the bud end (22%, 20%, respectively) which was significantly higher than R. Burbank, Clearwater R., and Ranger R. (16 to 18%). Dakota R. had the lowest shatter bruise incidence on the bud end (4%).

There was a significant (*P*<0.0001) effect between impact height and tuber end for all variables examined indicating the response to impact height differed by tuber end (Figure 4-4). The bud end had significantly less blackspot bruise incidence, severity, and depth at each impact height compared to the stem end. The difference in magnitude between the bud and stem end in blackspot bruise incidence and depth decreased with higher impact height (Figure 4-4a and c). Shatter bruise incidence did not differ between ends at 8 cm impact height (1%), but the bud end showed increased incidence at 18 cm impact height (13%) and 30 cm impact height (34%) compared to the stem end.

There was a significant effect between cultivar, impact height, and tuber end for blackspot bruise incidence (P=0.001) and shatter bruise incidence (P<0.0001; Figure 4-5). The bud end of these cultivars had greater variability in blackspot bruise incidence at 8 cm impact height (19 to 66%) compared to the stem end (56 to 91%). As impact height increased to 30 cm, there was less variability for blackspot bruise incidence for both ends (83 to 100%). Shatter bruise incidence remained low for the stem end (0 to 16%) for all cultivars between the impact heights. The bud end had greater variability in shatter bruise incidence at the 30 cm impact height between cultivars (9 to 50%).

Discussion

Blackspot and shatter bruise were greatly influenced by impact height in all russet cultivars examined. This conclusion agrees with previous research that cultivar and impact height are major influencers in bruise susceptibility (Corsini et al. 1999; Mathew and Hyde 1997; Partington et al. 1999; Thornton and Bohl 1995). To further illustrate how impact height influenced blackspot bruise susceptibility, a scale was modified from Sawyer and Collin's (1960) bruise index scale, which examined the average blackspot bruise incidence and severity ratings at each impact height presented in this study (Table 4-2). From this susceptibility scale, Clearwater R. and Dakota R. were moderately susceptible to blackspot bruise at the lowest impact height (8 cm), meaning management cannot rely solely on lowering impact heights in handling operations to lower bruise. Although for the other cultivars examined, lowering impact heights could be a very beneficial management tool. This scale also indicated that Umatilla R. and Teton R. are less susceptible to blackspot bruise formation even at higher impact heights. Using this scale illustrates how cultivar susceptibility is strongly reliant upon the impact height, either artificially via research techniques or from mechanical damage experienced in commercial situations. The categorization of a cultivar's bruise susceptibility level can be skewed if only one impact height is examined.

Shatter bruise susceptibility was determined by categorizing shatter bruise incidence into low (≤10%), moderate (11 to 25%), and high (≥26%) susceptibility (Table 4-3). Although susceptible to blackspot bruise, Dakota R. had extremely low shatter bruise susceptibility at each impact height examined. For this cultivar, additional research may allude to the physical, hereditary, or biochemical mechanisms that could explain why Dakota R. had low shatter bruise susceptibility. Teton R. had low shatter bruise susceptibility until the impact height reached 30 cm suggesting this cultivar has a critical failure point in the ability to resist shatter bruise. Lowering impact heights would be a good management strategy for shatter bruise when handling Teton R. Shatter bruise susceptibility was moderate at 18 cm impact height for Umatilla R., whereas the rest of the cultivars were low (Table 4-3). This higher susceptibility suggests Umatilla R. is more susceptible to shattering at lower impacts than the other cultivars examined. This data allows for cultivar-specific bruise management recommendations based upon handling and mitigating mechanical damage.

Xie et al. (2018) determined initial height of impact was a greater influencer on the depth of damage compared to tuber mass, tuber temperature and surface material tubers are dropped on, which corresponds with the response of bruise depth to impact height in this study. Bruise depth is crucial for quality inspection purposes. Inspection procedures include removing a small portion of the stem end of a tuber to inspect for blackspot bruise (USDA 2015). More severe bruises will extend deeper into the tissue which will lead to further investigation of internal quality concerns at time of inspection or could result in exceeding the allowable pare away tolerance. Lower impact heights resulted in shallower bruises for all cultivars, although Ranger R. had deeper bruises even at the lowest impact height compared to the other cultivars.

Differences in bruise susceptibility between the bud end and stem end were evident in all cultivars, which coincided with previous data (McGarry et al. 1996; Reeve et al. 1969). To test a cultivar or sample for bruise susceptibility it would be beneficial to impact both the bud end and stem end. This study found greater response on the bud end to varying impact heights for each cultivar compared to the stem end. The average blackspot bruise incidence ranged from 42 to 89% on the bud end between impact heights (47% variance) where the stem end ranged from 81 to 98% incidence (17% variance). The bud end also had greater variability for shatter bruise incidence (1 to 34%) compared to the stem end (1 to 6%) between impact heights. For each cultivar, the bud end had greater variability at the 8 cm impact height for blackspot bruise (19 to 66% incidence) and at the 30 cm impact height for shatter bruise (9 to 50% incidence). These conclusions suggest the difference in how the bud end responds to impact will influence overall bruise susceptibility more than the stem end.

Previous research examined biochemical components which may contribute to bruise susceptibility within a tuber. Tyrosine is considered a primary substrate for the formation of melanin (Belknap et al. 1990) a critical component in the development of blackspot bruise. Tyrosine has been reported to be 20 to 40% more concentrated in the stem end of the tuber as compared to the bud end (Reeve et al. 1969). Various cultivars have been found to have different concentrations of tyrosine and other phenolic substrates of PPO, which are active components in discoloration development (Stark et al. 1985). Stark et al. (1985) also emphasized that for bruise resistant cultivars, tyrosine was incorporated into proteins rather than being used in PPO activity. Rastovski and Es (1981) concluded that concentrations of chlorogenic acid, tyrosine, phenolase, peroxidase, catalase, ascorbic acid, acidity, and iron were higher in the stem end. The bud end was reported to have higher citric acid, phosphorus, potassium, and solanine-solanidine (Rastovski and Es. 1981). Yet, ascorbic acid has also been reported to be almost double on the bud end compared to the stem end (Smith and Gillies 1940). Mondy and Leja (1986) concluded bruised tissue had lower ascorbic acid present than unbruised tissue, and Lin et al. (2021) concluded ascorbic acid may inhibit PPO activity. There are some contradictions as to how certain biochemical components relate to bruise, as presented about ascorbic acid concentrations between the bud and the stem end but differing biochemical components may suggest why the bud end has lower blackspot bruise formation than the stem end. Cultivar biochemical differences may also indicate why Ranger R. had higher blackspot bruise severity levels than Umatilla R. even though their blackspot bruise incidence was similar.

The difference in shatter bruise response between tuber ends may be due to the unique cellular structure of the tuber. During plant growth, tuberization occurs at the stolon tip and includes rapid cell division and expansion (Xu et al. 1998). In the stem region (where the newest tissue is forming) the cells first enlarge then divide longitudinally, whereas in the bud region the cells divide transversally and then elongate (Xu et al. 1998). The way these cells divide during growth dictate how cell structure develops and may indicate why different areas of the tuber have different bruise susceptibility levels. Cellular structure may determine if intercellular membranes are disrupted (blackspot bruise), or cell walls break (shatter bruise) under impact stress. Cell size has also been found to vary between cultivars (Reeve et al. 1973; Konstankiewicz et al. 2002), which could explain some of the cultivar variation seen in this study. Future research should examine correlations between cell size, biochemical composition, and bruise susceptibility in multiple cultivars to further understand the mechanical properties involved in bruise susceptibility and differing points of failure between cultivars and impact heights.

Conclusion

When handling multiple cultivars, bruise management strategies need to adapt for each cultivar to keep bruise-free percentages high. Methods of lowering the impact height during harvest and handling operations are helpful tools to lower bruise incidence for R. Burbank, Ranger R., Teton R., and Umatilla R. For cultivars more sensitive to blackspot bruise, such as Clearwater R. and Dakota R., other tools such as appropriate pulp temperatures at handling may be more critical to integrate with lowering drop heights to maximize the percentage of bruise-free tubers. To test for bruise susceptibility, impacting both tuber ends can provide insight on the type of resulting bruise and using more than one impact height will provide greater awareness of the cultivars’ bruise susceptibility pattern. Higher impact heights can help determine susceptibility levels for shatter bruise whereas lower impacts can be more beneficial to understand blackspot bruise susceptibility of a certain cultivar. Research techniques need to adapt and include more than one impact height to develop a comprehensive bruise susceptibility level.

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Tables

Table 4-1. Effect of cultivar, impact height, and tuber end on blackspot and shatter bruise.

Main effect	Blackspot bruise incidence (%)[1]	Blackspot bruise severity rating (1-4) [2]	Blackspot bruise depth (mm)	Shatter bruise incidence (%)
Cultivar				
Russet Burbank	72 b	2.3 b	4.6 b	11 b
Clearwater Russet	88 d	2.6 d	5.1 c	9 b
Dakota Russet	89 d	2.7 e	5.8 d	3 a
Ranger Russet	81 c	2.5 d	5.1 c	10 b
Teton Russet	67 a	2.0 a	3.7 a	14 c
Umatilla Russet	79 c	2.4 c	4.5 b	11 b
P-value	<0.0001	<0.0001	<0.0001	<0.0001
Impact height (cm)				
8	62 a	1.7 a	2.9 a	1 a
18	83 b	2.4 b	4.9 b	7 b
30	94 c	3.1 c	6.6 c	20 c
P-value	<0.0001	<0.0001	<0.0001	<0.0001
Tuber end				
Bud	68 a	2.0 a	4.0 a	16 b
Stem	91 b	2.8 b	5.6 b	3 a
P-value	<0.0001	<0.0001	<0.0001	<0.0001

[1] Values followed by the same letter are not significantly different (α<0.05) for each parameter within each column.

[2] Blackspot bruise severity 1 to 4: 1= no color, slight cell deformation, 2=light gray color, not severe but discoloration occurred, 3=dark grayish color, severity is moderate, dark but not extreme, 4=dark gray/black color, severity is extreme.

Table 4-2. Blackspot bruise susceptibility scale and categorization as influenced by impact height and cultivar.

Blackspot bruise susceptibility scale[1]				Category[2]		
	Impact height (cm)			Impact height (cm)		
Cultivar	8	18	30	8	18	30
R. Burbank	20	44	68	Low	Moderate	High
Clearwater R.	36	60	80	Moderate	Moderate	High
Dakota R.	37	63	83	Moderate	Moderate	High
Ranger R.	29	55	76	Low	Moderate	High
Teton R.	14	36	61	Low	Moderate	Moderate
Umatilla R.	28	49	66	Low	Moderate	Moderate

[1] Blackspot bruise susceptibility scale is modified from Sawyer and Collin (1960) bruise index scale that takes into consideration the average blackspot bruise incidence and average severity rating. The severity scale is on a 1 to 4 scale. The formula is (percentage of blackspot bruise*severity rating)/4. Bruise susceptibility scale is from 0 to 100 with 0 being the least susceptible and 100 being the most susceptible.

[2] Categories were determined by low, moderate, or high blackspot bruise severity with 0 to 33 being low, 34 to 66 being moderate, and 67 to 100 being high.

Table 4-3. Shatter bruise susceptibility and categorization as influenced by impact height and cultivar.

Shatter bruise incidence (%)				Category[1]		
	Impact height (cm)			Impact height (cm)		
Cultivar	8	18	30	8	18	30
R. Burbank	2	8	22	Low	Low	Moderate
Clearwater R.	1	6	21	Low	Low	Moderate
Dakota R.	1	2	6	Low	Low	Low
Ranger R.	1	9	20	Low	Low	Moderate
Teton R.	1	7	33	Low	Low	High
Umatilla R.	1	11	20	Low	Moderate	Moderate

[1] Shatter bruise susceptibility was categorized by shatter bruise incidence; low = ≤10%, moderate = 11 to 25%, high = ≥26%.

Figures

Figure 4-1. Blackspot bruise severity was rated on the darkest color observed on a scale from 1 to 4: 1= no color, 2=light gray color, not severe but discoloration occurred, 3=dark gray color, severity is moderate, dark but not extreme, 4=dark gray/black color, severity is extreme.

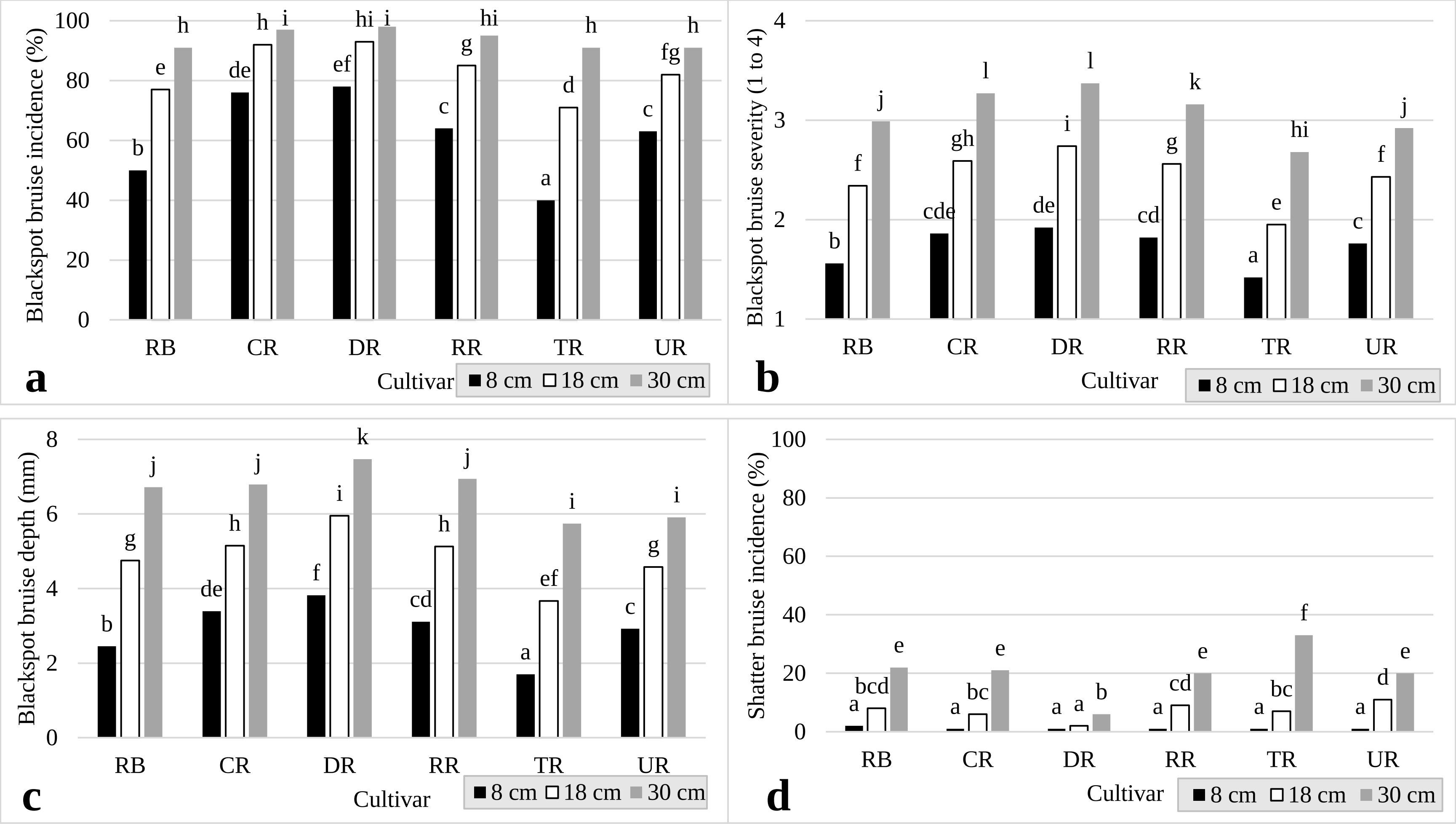

Figure 4-2. Effect of cultivar (RB: Russet Burbank; CR: Clearwater Russet; DR: Dakota Russet; RR: Ranger Russet; TR: Teton Russet; UR: Umatilla Russet) and impact height on a) blackspot bruise incidence, b) bruise severity, c) bruise depth, and d) shatter bruise incidence. Blackspot bruise severity was rated on the darkest color observed on a scale from 1 to 4: 1= no color, 2=light gray color, not severe but discoloration occurred, 3=dark gray color, severity is moderate, dark but not extreme, 4=dark gray/black color, severity is extreme. Values followed by the same letter are not significantly different (α<0.05) for each graph.

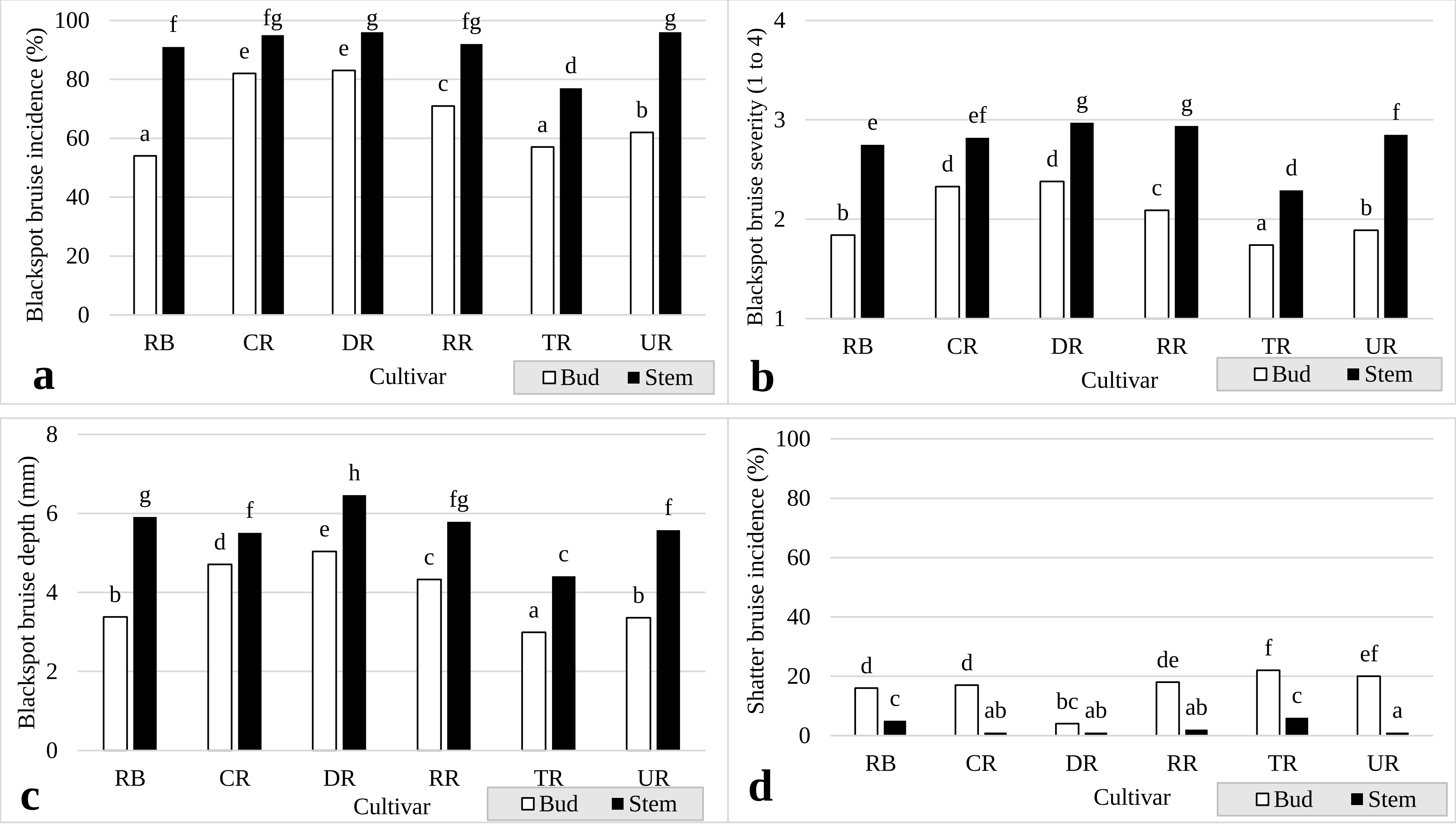

Figure 4-3. Effect of cultivar (RB: Russet Burbank; CR: Clearwater Russet; DR: Dakota Russet; RR: Ranger Russet; TR: Teton Russet; UR: Umatilla Russet) and tuber end on a) blackspot bruise incidence, b) bruise severity, c) bruise depth, and d) shatter bruise incidence. Blackspot bruise severity was rated on the darkest color observed on a scale from 1 to 4: 1= no color, 2=light gray color, not severe but discoloration occurred, 3=dark gray color, severity is moderate, dark but not extreme, 4=dark gray/black color, severity is extreme. Values followed by the same letter are not significantly different (α<0.05) for each graph.

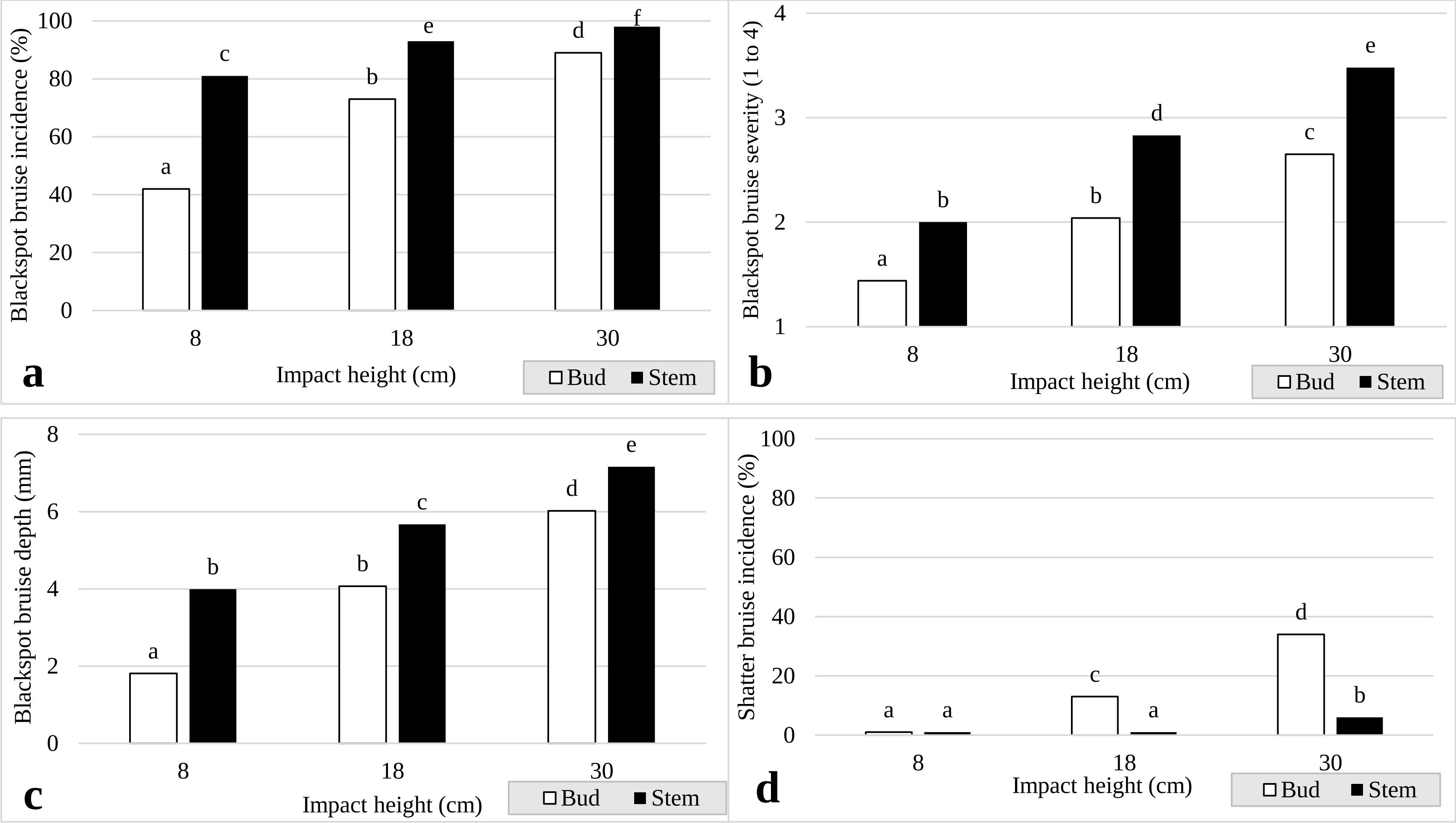

Figure 4-4. Effect of impact height (cm) and tuber end on a) blackspot bruise incidence, b) bruise severity, c) bruise depth, and d) shatter bruise incidence. Blackspot bruise severity was rated on the darkest color observed on a scale from 1 to 4: 1= no color, 2=light gray color, not severe but discoloration occurred, 3=dark gray color, severity is moderate, dark but not extreme, 4=dark gray/black color, severity is extreme. Values followed by the same letter are not significantly different (α<0.05) for each graph.

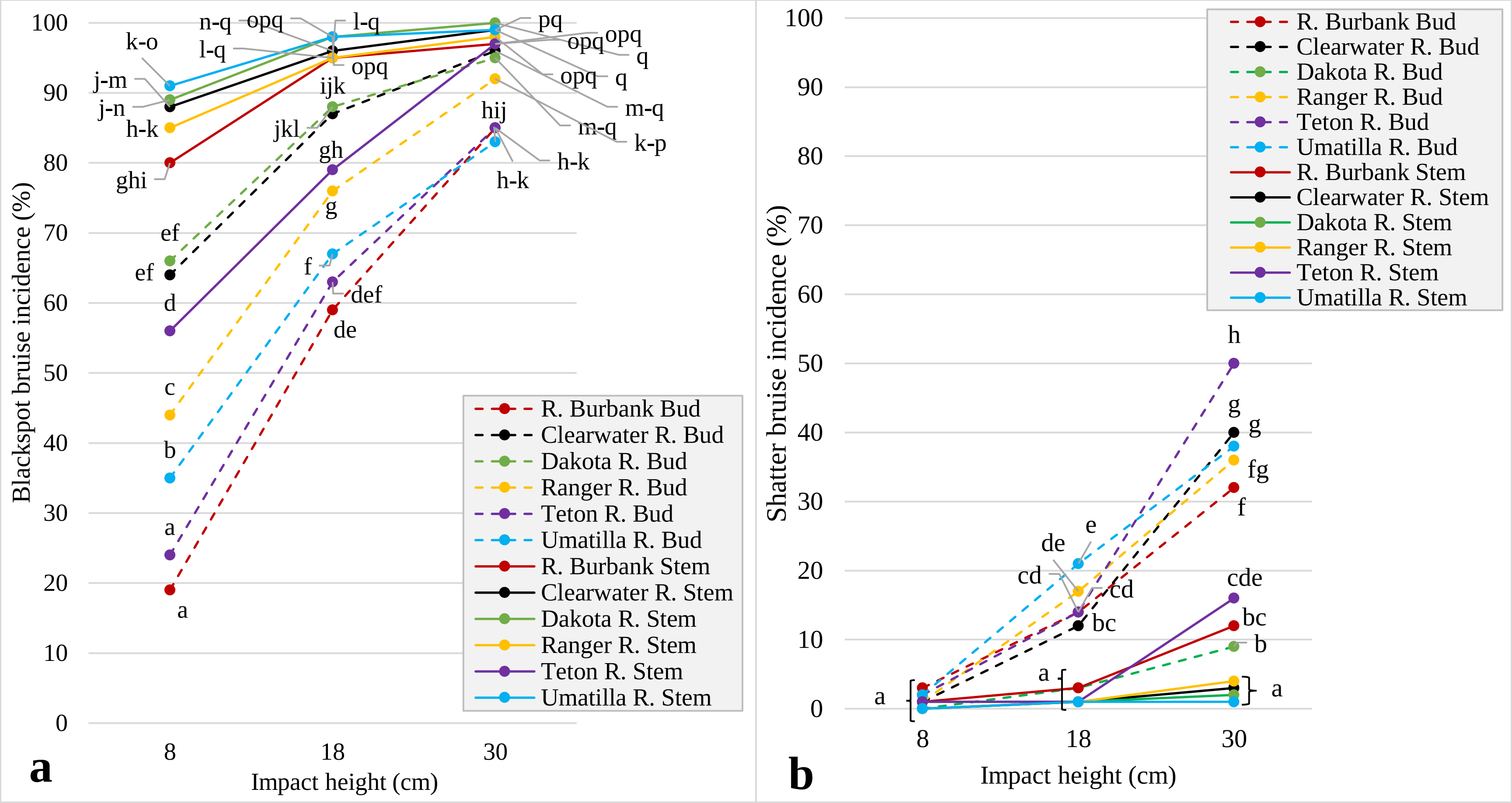

Figure 4-5. Effect of impact height (cm), cultivar (R. = Russet), and tuber end (stem or bud) on a) blackspot bruise incidence, and b) shatter bruise incidence. Blackspot bruise severity was rated on the darkest color observed on a scale from 1 to 4: 1= no color, 2=light gray color, not severe but discoloration occurred, 3=dark gray color, severity is moderate, dark but not extreme, 4=dark gray/black color, severity is extreme. Values followed by the same letter are not significantly different (α<0.05) for each graph.

Chapter 5: Simulated Scenario: Use of Impact Recording Device in Packaged Shipments of Potatoes

Abstract

Handling potatoes individually or collectively in packages, can create opportunities for potatoes to develop blackspot and shatter bruise and cause quality defects. Three trials were conducted to examine how package handling can influence the risk for physical damage and bruise. An impact recording device was used to record peak acceleration (max g-force) in common fresh market packaging options (boxes or bales) at four drop heights on to different surface types. When boxed potatoes were dropped on to concrete or a plastic slip from heights of 15 to 91 cm, the potatoes on the bottom of the box had the highest risk of damage (greater than 100 g-force). The risk for damage was lower for potatoes in the top or middle of the box. When drop heights were lowered, or when cushioning material was added to hard surfaces (wooden pallet), the risk for impact damage was decreased throughout the box. When palletizing boxed potatoes, the risk of bruise decreased after the first layer was stacked on the pallet. The risk of high peak accelerations (over 100 g-force) was not seen in the dropped or stationary bales for any of the drop heights examined. Increased cushioning for the bottom stack of potatoes during palletization in fresh pack facilities could lower the risk of bruise. Cushioned plastic slips could provide an economical and efficient alternative to wooden pallets. Results determined drop heights need to be below 15 cm, especially when making the first layer in a palletized stack of packaged potatoes. This study provided information for fresh pack facilities to educate personnel on handling packaged potatoes and determine when robotics need to be adjusted to lower drop heights of packaged potatoes.

Introduction

U.S. potato yields increased by 7,900 kg per acre between 1984 and 2019 (USDA 1999; USDA 2020). This increase in production has demanded the ability to handle a greater volume of potatoes in the same timeframe each year. Harvesting and handling operations have become more reliant on machinery and automation rather than manual labor to efficiently harvest, sort, transport, wash, and package potatoes. Minimizing quality losses is crucial in all post-harvest operations. Quality losses can be the result of bruises sustained during handling operations. Bruises occur as a result of major and minor physical impacts when tubers contact equipment components, change direction, or drop from conveyor belts onto different surfaces (Bentini et al. 2006; Hyde et al. 1988). There are two major types of bruises: blackspot and shatter bruise. McGarry et al. (1996) indicated higher impact heights will result in shatter bruise, while lower impacts tend to cause blackspot bruise formation. One way to ensure bruise is minimized is to monitor and adjust equipment during harvest and handling operations in areas of high bruise probability. A tool used for assessing the risk of physical damage and bruise potential during handling is an instrumented sphere or impact recording device (IRD; Praeger et al. 2013). IRDs can be used in potato and other commodities concerned with impact related injuries such as apples, citrus fruit, tomatoes, and bell peppers (Pason et al. 1990; Pothula et al. 2018; Manetto et al. 2017; Sargent et al. 1992). The device can be placed on a piece of equipment to measure and record the acceleration and mimic how a potato (or another commodity) could potentially be impacted. IRDs can record peak acceleration, velocity change, number of impacts endured, and provide a time stamp for each data point, although not all models include velocity change (Hollingshead et al. 2020). Peak acceleration is reported as g-force (1 g = 9.8 m/s^2). The higher the peak acceleration, the greater the potential for physical damage and bruising. Hyde et al. (1992) established bruise thresholds with an IRD to help understand the measurements that are recorded. Bruise potential was high when peak acceleration was above 100 g and peak accelerations over 375 g would likely cause visible damage (Hyde et al. 1992). These values (100 to 375 g) are used throughout this study to help determine the risk associated with impact heights, packaging materials and impact force. Velocity change (m/s) is calculated based on the area under the acceleration curve versus time and accounts for surface type tubers are dropped on and magnitude of impact (Hollingshead et al. 2020; Rady and Soliman 2015; Molema et al. 2000). The acceleration curve (Figure 5-1, adapted from Molema et al. 2000) is an example of how the velocity change and peak acceleration contributes to impact force. Collectively, these measurements indicate equipment or areas on the equipment that may increase the risk for bruising. Typically, the IRDs will indicate large drop heights and/or drops onto hard materials, and then mechanical adjustments can be made based upon the IRD measurements.

Mass of an object, drop height, and surface type tubers are dropped on are the major components involved in determining peak acceleration and the velocity change experienced at time of impact (Deng et al. 2020; Thomson and Lopresti 2018). Drop height and surface type tubers are dropped on can be adapted in a handling operation to lower the impact force. To modify handling operations, the IRD can be first used to identify the drop heights and surface types that elevate the risk of physical damage to the potatoes. Decreasing drop heights as tubers transition from one surface to another can minimize damage throughout post-harvest equipment and cushioning surface types allow for greater drop heights before physical damage occurs. Using the two methods in unison can reduce the potential for impact damage. Rady and Soliman (2015) conducted drop tests with potatoes and measurements from an IRD and found drop heights exceeding 15 cm onto steel surfaces caused damage, but after affixing a rubber coating to the steel surface, drop heights could be increased to 25 cm before causing damage. In addition, tubers could be dropped up to 90 cm onto a layer of other tubers before damage occurred. Surface type tubers are dropped on and drop height together can help determine bruise potential of potato tubers. An IRD does not consider bruise susceptibility of the individual tuber, but rather measures the potential impact force a potato will encounter as it is handled.

Fresh market potatoes are the number one fresh vegetable sold in the United States (US; Karst 2019) and accounted for 23% of the total 2019 potato utilization in US (USDA 2020). Potatoes are unloaded at a fresh packing facility to be washed, sorted and packaged into various bag sizes or into bulk containers. This additional handling to prepare potatoes for shipment can cause further physical damage. IRDs have been deployed through fresh pack facilities to measure if additional bruising may arise beyond what occurred at harvest (Klug et al. 1989). Once potatoes are packaged, there is less bulk handling involved and IRDs are not commonly used for assessment at this stage. Bulk or bagged potatoes are collectively put together to form a larger packaged unit of a box or bale. Once packaged into paper bales or bulk cardboard boxes, potatoes must be palletized prior to transportation. Operations can use manual labor at this stage or have automated or robotic machinery that stack boxes or paper bales (often 22.7 kg) on to plastic slips or pallets. The boxes often hold loose potatoes whereas baled packaging includes 2.3 or 4.5 kg individually bagged potatoes. This study examined if this last stage in packaging and palletizing at a fresh pack facility was contributing to bruise and quality issues prior to transit. Previous research examined simulated transportation equipment for packaged potatoes and concluded shatter bruise can be caused by rough handling of packaged potatoes (Turczyn et al. 1986). Pason et al. (1990) used an IRD in shipments of apples to examine potential damage that occurred during transit although packages were not intentionally dropped. Most IRDs are placed on operating equipment, whereas Pason et al. (1990) provided context and validity for using an IRD in packaged containers rather than on equipment. The objective of this study was to evaluate drop height and surface type packages were dropped on and their potential effect on bruise potential of packaged potatoes utilizing an IRD in simulated scenarios of preparing potatoes for shipment.

Methods and Materials

Summary of Trials

Three trials were conducted to simulate the final stage of the packing line at a fresh packing facility. An IRD (Techmark, Inc., Lansing MI) was placed inside packaged potatoes to determine bruise potential. The IRD detects impacts with a tri-axial accelerometer and can determine impact amplitude +/- 500 g with 3% accuracy. The IRD records the peak acceleration as maximum g force (1 g = 9.8 m/s^2) and the change in velocity. The change in velocity accounts for the impact surface and the magnitude of the impact. Trial one focused on boxed potatoes when dropped from various heights and on to differing impact surfaces. Trial two focused on boxed potatoes when being placed on a wooden pallet. Trials three focused on baled potatoes when being placed on a wooden pallet. Each trial was conducted twice.

The packaging materials used were a 22.7 kg cardboard box (48 x 30 x 23 cm) or a 22.7 kg paper bale. The bale was a thick brown paper bag and held five, 4.5 kg store-ready plastic bags. The cardboard box held loose potatoes. The potatoes and packaging were sourced from a local fresh pack facility.

The first trial examined the peak acceleration measured by the IRD in a 22.7 kg box of potatoes when dropped from four different heights on to three surfaces. The IRD was either placed in the bottom, the middle, or the top layer of the box (three locations). The middle layer was defined as having at least one layer of potatoes underneath the IRD. The box was then dropped from 15, 30, 61, and 91 cm. Distance was measured from the bottom of the box to the top of the surface before being dropped. The box was dropped on to a concrete floor, a wooden pallet, or a plastic slip sheet. The plastic slip and wooden pallet were placed on top of the concrete floor. This trial was set up as a three by three by four factorial experiment and each treatment was replicated six times.

Trial two examined the peak acceleration measured by the IRD in 22.7 kg boxes of potatoes when one box was dropped on to another box at different heights. The IRD was placed either in the bottom, the middle, or the top layer of the box (Figure 5-2). The IRD recorded impacts from the box being dropped (Box A) as well as the stationary box (Box B). Box B was placed on a wooden pallet. Box A was dropped from 15, 30, 61, and 91 cm. Distance was measured from the bottom of Box A to the top of Box B before being dropped.

Trial three examined the peak acceleration measured by the IRD in 22.7 kg bales of potatoes when dropped from different heights on to a wooden pallet or other bales (Figure 5-3). The IRD was placed in the middle of the bale between two 4.5 kg bagged potatoes. There were three bales included in this trial. One bale was dropped on to a wooden pallet from 15, 30, 46, 61, and 91 cm. The next treatment had a stationary bale on the wooden pallet and an additional bale was dropped onto the stationary bale at the previously mentioned heights. The final treatment had two stationary bales on the wooden pallet and a third bale was dropped on top of these bales from the previously mentioned heights.

Statistical Analysis

Peak acceleration was analyzed using the ANOVA procedures in R (RStudio, package car version 3.0-9, 2020; Fox and Weisberg 2019). A linear model was fit for trial one where impact surface, drop height, IRD placement and the interactions were considered fixed effects. For trials two and three placement of IRD, drop height and the interactions were considered fixed effects for the linear models. All trials' significant differences between means for response variables were compared at alpha of 0.05 by estimated marginal means procedures (RStudio, package emmeans version 1.6.1, 2020; Lenth 2021). Impact was summarized in terms of average peak acceleration. Trial one also summarized the average velocity change to help determine bruise potential.

Results

Peak acceleration of IRD in box dropped from different heights and surfaces: Trial one.

Peak acceleration measured by the IRD was significantly (P<0.0001) influenced by the drop height of the box, the impact surface, and the IRD placement within the box (Table 5-1). Peak accelerations ranged from 37 to 446 g depending on the impact surface, drop height or IRD placement. As drop height increased, peak acceleration increased incrementally (90 g at 15 cm to 247 g at 91 cm). Dropping a box on to a wooden pallet showed a significantly lower peak acceleration (132 g) than a plastic slip (188 g) or concrete floor (204 g; Table 5-1). Dropping the box on to the concrete floor had the highest peak acceleration. IRD location in the box influenced the peak acceleration recorded. The bottom of the box experienced a higher peak acceleration (315 g) compared to the middle (116 g) and top of the box (93 g; Table 5-1). The interaction between IRD location in the box and the impact surface was significant (P<0.0001). The greatest difference in peak acceleration among the three materials occurred when the IRD was placed at the bottom of the box. When the IRD was located at the bottom of the box and dropped on to the pallet, the peak acceleration was 124 g which was approximately 136 g’s less than dropping the box onto the plastic slip (359 g) or concrete floor (361 g; Figure 5-4). This indicated no significant difference between the concrete impact surface and the plastic slip in potential impact forces experienced at the bottom of the box. The top and middle of the box had less variability in peak acceleration between surfaces. Although there was significantly higher peak acceleration in the middle of the box (147 g) when dropped on to a concrete floor compared to the wooden pallet (93 g) or plastic slip (109 g). When the IRD was placed in the top of the box, peak acceleration was significantly lower than the middle or bottom of the box for all impact surfaces (80 to 103 g). Boxed potatoes dropped on the concrete surface experienced a larger increase in peak acceleration with increasing drop height (108 to 281 g) compared to being dropped on either the slip (106 to 247 g) or wooden pallet (56 to 214 g; Figure 5-5). Likewise, the largest increase in peak acceleration with increasing drop height occurred when the IRD was place in the bottom of the box (173 to 421 g), with much less response in the middle (54 to 177 g) and top (43 to 144) locations (Figure 5-6). The three-way interaction for peak acceleration between drop height, impact surface, and placement within the box was significant (P <0.001; Figure 5-7). The peak acceleration when the IRD was placed in the top of the box was similar when dropped at each drop height onto the pallet, slip and concrete. When the IRD was placed in the middle of the box, the peak acceleration was similar at the lower drop heights among the different impact surfaces.

Although peak acceleration was much higher on concrete compared to the slip and pallet when the IRD was placed in the middle of the box and dropped from the two highest drop heights (61 and 91 cm). Peak acceleration when the IRD was placed in the bottom of the box was similar between the concrete and slip as the drop height increased, whereas the bottom of the pallet had much lower peak accelerations at all drop heights until the highest drop.

The IRD used in this trial recorded the velocity change (m/s) as well. The relationship between peak acceleration and velocity change is described in Figure 5-8. Figure 5-8 used Hyde et al. (1992) damage reference points (100 to 375 g) to examine the bruise damage potential potatoes could experience when boxes were dropped at different heights, on to different surfaces, and location within the box. Bruise potential was lowest for the potatoes in the top of the box when boxes were dropped from 15 cm on to a wooden pallet, whereas the highest potential for bruise occurred in the bottom of the box, dropped from 91 cm on to concrete or a plastic slip. These are the extreme scenarios. Drop heights above 15 cm account for most of the potential damage for the drop height variable. Although the bottom of the box is the most likely to experience damage, the top and middle of the box can still range in the damage potential zone. Any impact surface has the potential to cause bruise damage at higher drop heights.

Peak acceleration of IRD of boxed potatoes dropping on boxed potatoes: Trial two.

Overall, no peak acceleration force exceeded 100 g for this trial. Significant differences (*P*=0.04) in peak accelerations due to treatment and drop height were observed. There were significant differences in peak acceleration when the IRD was placed in the bottom of the stationary box (32 g) compared to the top of the stationary box (49 g). Peak acceleration was similar in the dropped box (39 to 43 g) regardless the placement of the IRD (Table 5-2). Peak acceleration incrementally increased as drop height increased (20 to 63 g; Table 5-2). There was a significant interaction in peak acceleration between treatment and drop height (*P* = 0.0005). The treatments had more variability in peak acceleration at the 91 cm drop height (44 to 85 g) compared to the 61 cm drop height (38 to 59 g) or the 30 cm drop height (24 to 50 g). No significant differences among the six treatments were observed at the 15 cm drop height (14 to 25 g; Figure 5-9).

Peak acceleration of IRD when a bale is dropped at various heights: Trial three.

This trial examined peak accelerations when a bale of potatoes was dropped on to a pallet or other bales of potatoes (Figure 5-3). Overall, peak acceleration force did not exceed 60 g for this trial and there were no significant differences (P=0.09) between treatments (Table 5-3). Peak acceleration significantly increased as drop height increased (21 to 58 g; Table 5-3). There was no significant interaction between treatment and drop height (P=0.87).

Discussion

Although IRDs are intended to mimic the potential for a damaging impact force to an individual tuber as it moves through handling equipment, this study used the IRD to gather information about how a potato within a box or bale of potatoes would respond to being dropped. Peak acceleration and velocity change have been used in previous studies to develop bruise risk management strategies. Praeger et al. (2013) found peak acceleration is a practical tool to determine whether potatoes in handling operations are surpassing a bruise threshold. Hyde et al. (1992) determined bruise potential is low when peak acceleration is below 50g, high when peak acceleration is above 100 g, and definite damage occurs over 375 g. When recorded peak acceleration is within the major bruise potential zone (between 100 and 375 g), the next step is to determine how to minimize the large impacts.

One caveat about IRD technology is that it only measures impact force, not tuber characteristics, which may also influence bruise susceptibility and how the tuber responds to the impact force. Previous research has identified methods to determine bruise thresholds using an IRD (Bajema and Hyde 1998; Hyde et al. 1992; Mathew and Hyde 1997; Rady and Soliman 2015). A bruise threshold is defined as the impact force required to damage a potato, but tuber pulp temperature, (Thornton et al. 1973; Smittle et al. 1974; McGarry et al. 1996; Baritelle and Hyde 2001; Xie et al. 2020), cultivar (Blahovec and Židová 2004; Kunkel et al. 1978; Horvath 1986), and tuber hydration (Kunkel and Gardner 1965; Thornton and Timm 1990) are examples of factors that can alter bruise susceptibility and influence the bruise threshold. Rather than create a bruise threshold, this study provided contextual data to aid in determining package handling scenarios that could increase the risk for bruise.

Boxes dropped on to a concrete floor, or a plastic slip over a concrete floor, have the highest risk of damage, especially for potatoes in the bottom of the box. The potatoes at the bottom of the box will encounter a peak acceleration of 200 g even at a low drop height of 15 cm. The risk of damage is lower for potatoes in the top or middle of the box. When drop heights were lowered, or when cushioning material was added to a hard surface (like a wooden pallet), risk of damage decreased throughout the box. However, all drop heights and impact surfaces evaluated in this study had the potential to cause damage to potatoes located throughout the box. The combination of all three variables will dictate the severity of damage. For instance, the top and middle of the box were less likely to experience damage when dropped from heights below 30 cm on any impact surface. When the drop height was increased to 61 to 91 cm, these potatoes were more likely to experience damage, regardless of the surface. Potatoes in the bottom of the box were less likely to experience damage when potatoes were dropped from 15 cm and on to a wooden pallet. Regardless of the impact surface, the potatoes on the bottom of the box have an increased risk of damage. When palletizing boxed potatoes, the risk of bruise decreased after the first layer was stacked on the pallet. This result reinforced the importance of modifying the potential impact packaged potatoes experienced on the initial layer of the pallet. The main issue was not subsequent packing of boxes on top of each other but rather the initial box being dropped on the concrete floor, plastic slip, or wooden pallet. For the initial layer during palletization of boxed potatoes, avoid dropping boxes more than 15 cm regardless of impact surface. Peak accelerations did not exceed 100 g's when packaged potatoes were dropped on to other boxes and/or bales reinforcing the concept that potatoes can withstand greater impact when dropped onto other potatoes as concluded by Rady and Soliman (2015).

The risk of high peak accelerations was not seen in the dropped or stationary bales for any of the drop heights examined. In a paper bale, potatoes are packaged tightly within the bale unlike boxes where potatoes are loose and have greater potential for movement within the box. The tighter packaging in paper bales could explain the overall low peak accelerations observed. Although, Turczyn et al. (1986) found cardboard boxes provided greater protection against shatter bruise than a paper bale. This contradictory finding suggests the IRD may have been unable to fully measure the impact of bagged potatoes packaged in a paper bale, and future research could further examine the relationship between the IRD findings and quantified damage of the potatoes in paper bales.

A wooden pallet was used as a cushioning material for this study and was found to soften the impact compared to a concrete floor or a plastic slip. Wooden pallets are used worldwide to transport goods but can be an additional cost to the supplier due to purchasing, sorting, and inspecting for damage (Mumford 2002). The plastic slip used in this study provided slightly better protection from damage over the concrete floor, except for potatoes at the bottom of the box. There was no difference between the plastic slip and concrete floor at lower drop heights, but this protection could be seen at the 61 and 91 cm drop heights. Modifying the plastic slip to include greater cushioning potential could provide an alternative for wooden pallets.

Conclusion

As fresh market potatoes are packaged into boxes or bales and placed on pallets there is potential for bruise to occur. This bruise potential is minimized as boxes and bales are dropped from lower heights and cushioned with the use of wooden pallets; although, the potatoes at most risk for bruise are in the bottom of the boxes. Increased cushion for the bottom stack of potatoes during palletization in fresh pack facilities could lower the risk of bruise. This study provided information for fresh pack facilities to educate personnel on handling packaged potatoes and adjust robotic palletizing machines. In addition, it determined drop heights need to be below 15 cm, especially when making the first layer in a palletized stack of packaged potatoes, to reduce the risk of bruise damage.

Cushioned plastic slips could provide an alternative to wooden pallets. Future research should assess visual damage that occurs when boxes and bales are dropped to further explain the risk associated with improper handling of packaged potatoes.

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Tables

Table 5-1. Mean peak accelerations (max g-force) as measured by an impact recording device (IRD) located in a potato box and dropped from multiple heights onto three different impact surfaces. Values followed by the same letter are not significantly different ($\alpha<0.05$) for each column.

Drop height (cm)	Peak Acceleration (g)[1]	
15	90	a
30	153	b
61	209	c
91	247	d
P-value	<0.0001	
Impact surface		
Wooden Pallet	132	a
Plastic Slip	188	b
Concrete	204	c
P-value	<0.0001	
Placement of IRD in box		
Top	93	a
Middle	116	b
Bottom	315	c
P-value	<0.0001	

[1] Values followed by the same letter are not significantly different ($\alpha<0.05$).

Table 5-2. Mean peak accelerations (max g-force) as measured by an impact recording device (IRD) located in a potato box dropping on additional boxed potatoes for multiple heights.

Treatment	Peak Acceleration (g)[1]	
Dropped box; IRD-top	43	bc
Dropped box; IRD-middle	39	ab
Dropped box; IRD-bottom	42	bc
Stationary box; IRD-top	49	c
Stationary box; IRD middle	39	ab
Stationary box; IRD bottom	32	a
P-value	0.04	
Drop height (cm)		
15	20	a
30	35	b
61	45	c
91	63	d
P-value	<0.0001	

[1] Values followed by the same letter are not significantly different ($\alpha<0.05$) for treatment and drop height.

Table 5-3. Mean peak accelerations (max g-force) as measured by an impact recording device (IRD) located in a paper bale and dropped from multiple heights.

Treatment	Peak Acceleration (g)[1]	
Bale dropped onto wooden pallet; IRD in dropped bale	47	
Bale dropped onto stationary bale; IRD in dropped bale	46	
Bale dropped onto two stationary bales; IRD in dropped bale	38	
Bale dropped onto stationary bale; IRD placed in stationary bale	43	
Bale dropped onto two stationary bales; IRD in top stationary bale	57	
Bale dropped onto two stationary bales; IRD in bottom stationary bale	20	
P-value	0.09	
Drop height (cm)		
15	21	a
30	32	ab
48	45	bc
61	53	c
91	58	c
P-value	0.002	

[1]Values followed by the same letter are not significantly different ($\alpha<0.05$) for treatment and drop height.

Figures

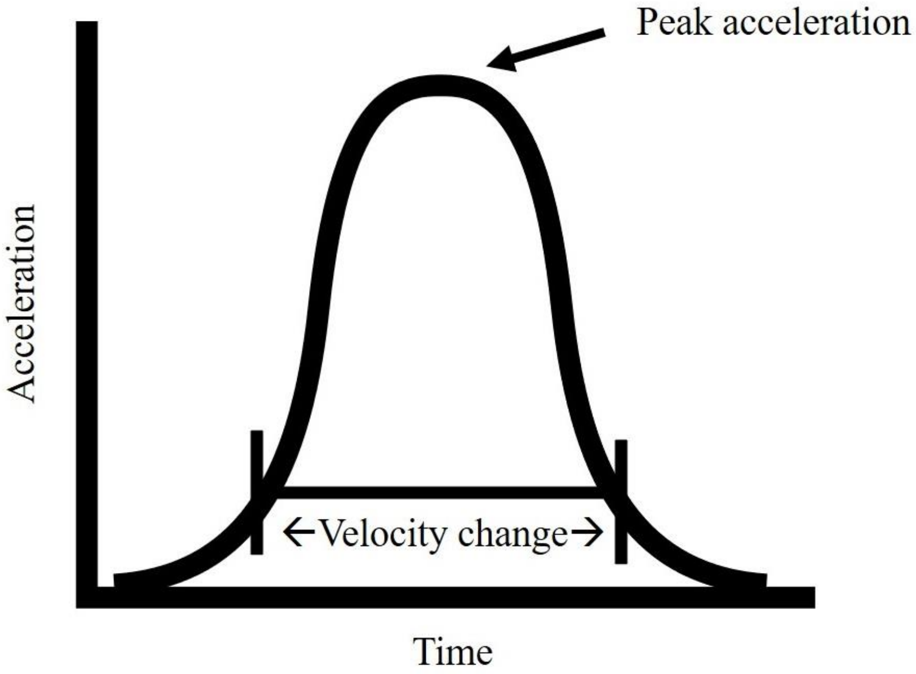

Figure 5-1. Representation of an impact. Adapted from Molema et al. 2000.

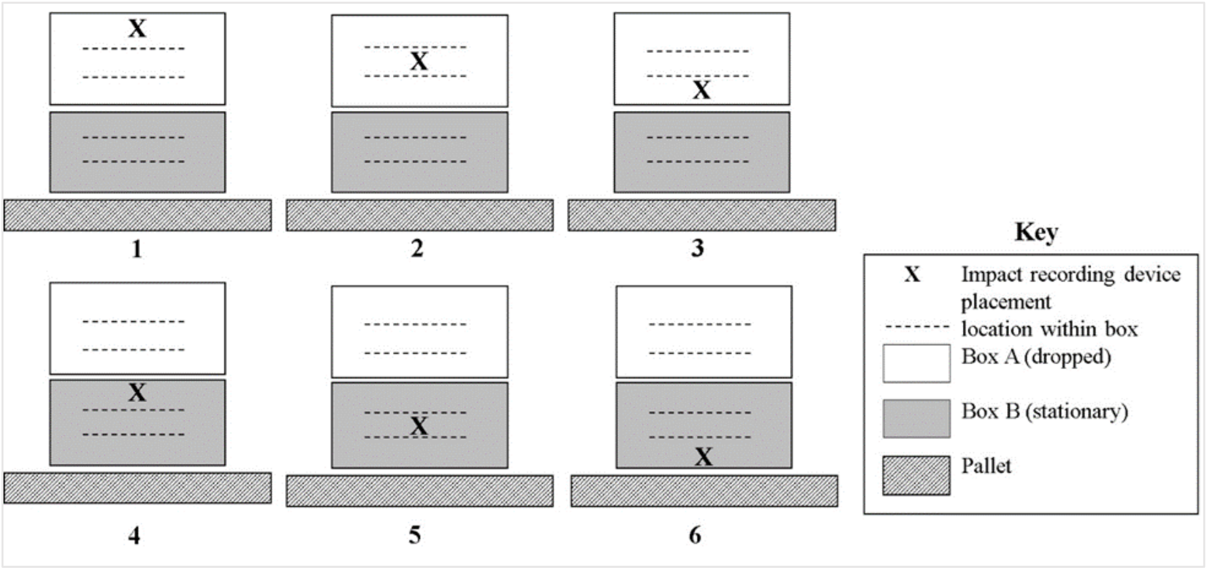

Figure 5-2. Trial two treatments. All treatments were dropped onto wooden pallet, at 15, 30, 61 and 91 cm six times. 1) Impact recording device (IRD) placed in the top of the dropped box, 2) IRD placed in the middle of the dropped box; 3) IRD placed in the bottom of dropped box, 4) IRD placed in the top of the stationary box, 5) IRD placed in the middle of the stationary box, 6) IRD placed in the bottom of the stationary box.

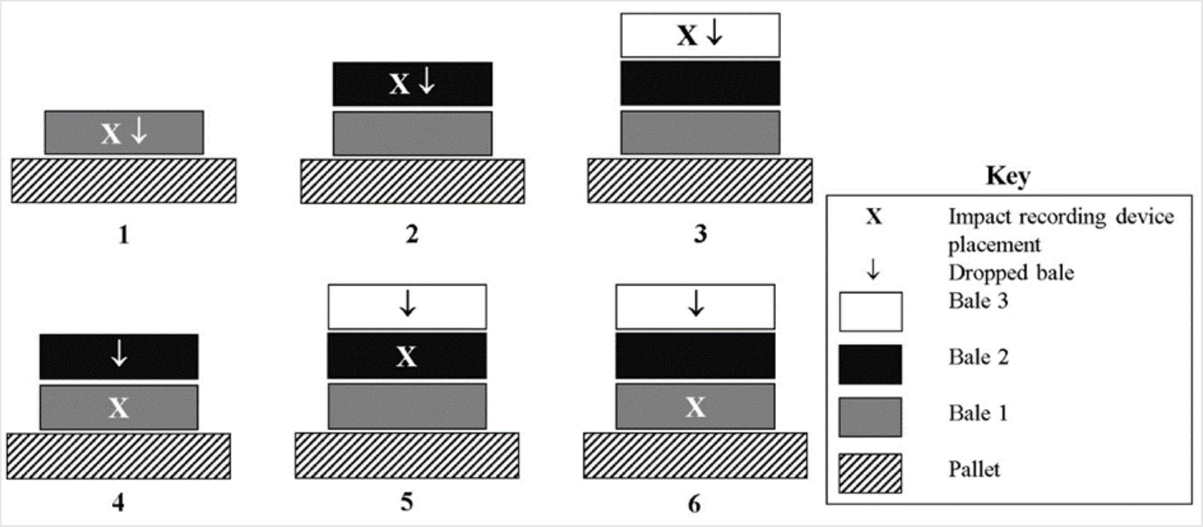

Figure 5-3. Trial three treatments: 1) one bale dropped onto wooden pallet, impact recording device (IRD) placed in bale; 2) one bale dropped onto stationary bale, IRD placed in dropped bale; 3) one bale dropped onto two stationary bales, IRD placed in dropped bale; 4) one bale dropped onto stationary bale; IRD placed in stationary bale, 5) one bale dropped onto two stationary bales, IRD placed in top stationary bale, 6) one bale dropped onto two stationary bales, IRD placed in bottom stationary bale. Each treatment was carried out at 15, 30, 46, 61 and 91 cm heights six times.

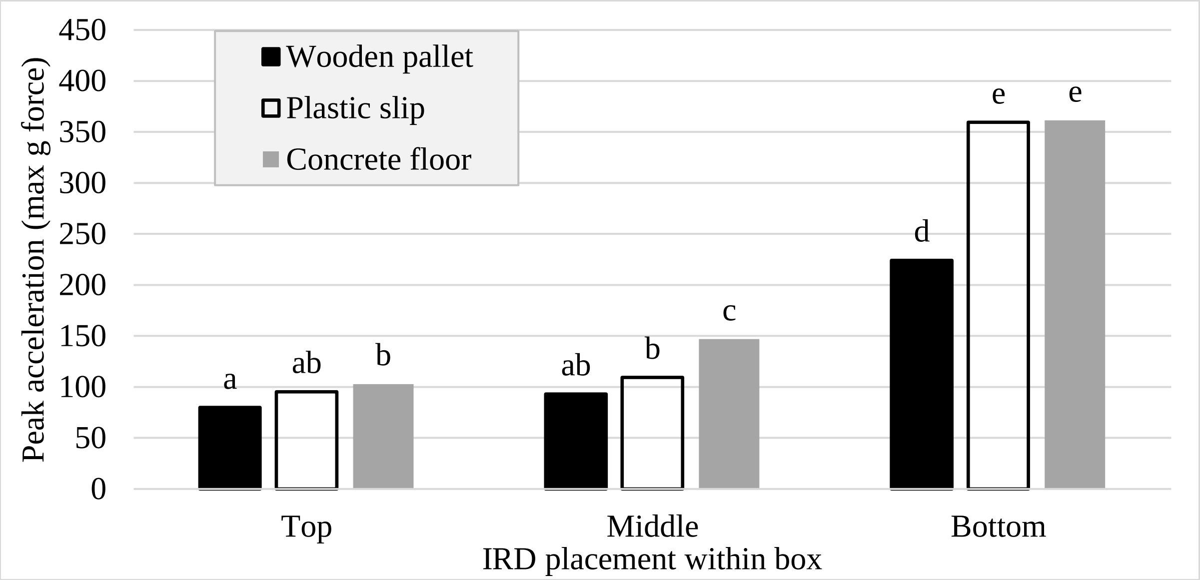

Figure 5-4. Peak acceleration of the impact recording device (IRD) as influenced by placement within the box (top, middle, bottom) and impact surface (wooden pallet, plastic slip, concrete floor). Values followed by the same letter are not significantly different (α<0.05).

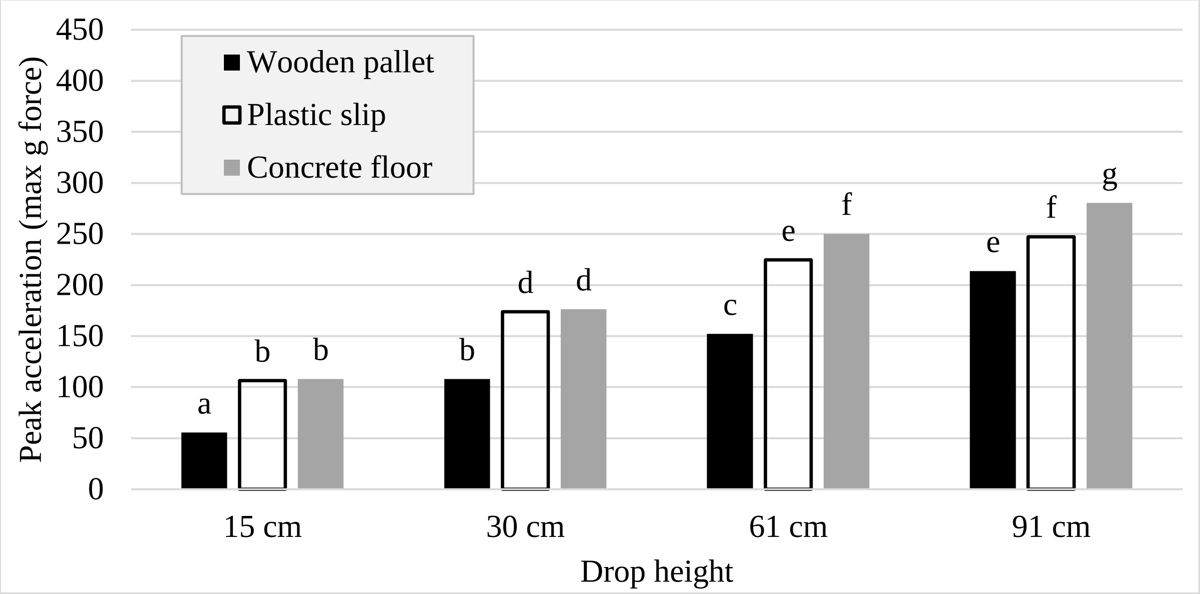

Figure 5-5. Peak acceleration of the impact recording device (IRD) as influenced by drop height (15, 30, 61, 91 cm) and impact surface (wooden pallet, plastic slip, concrete floor). Values followed by the same letter are not significantly different (α<0.05).

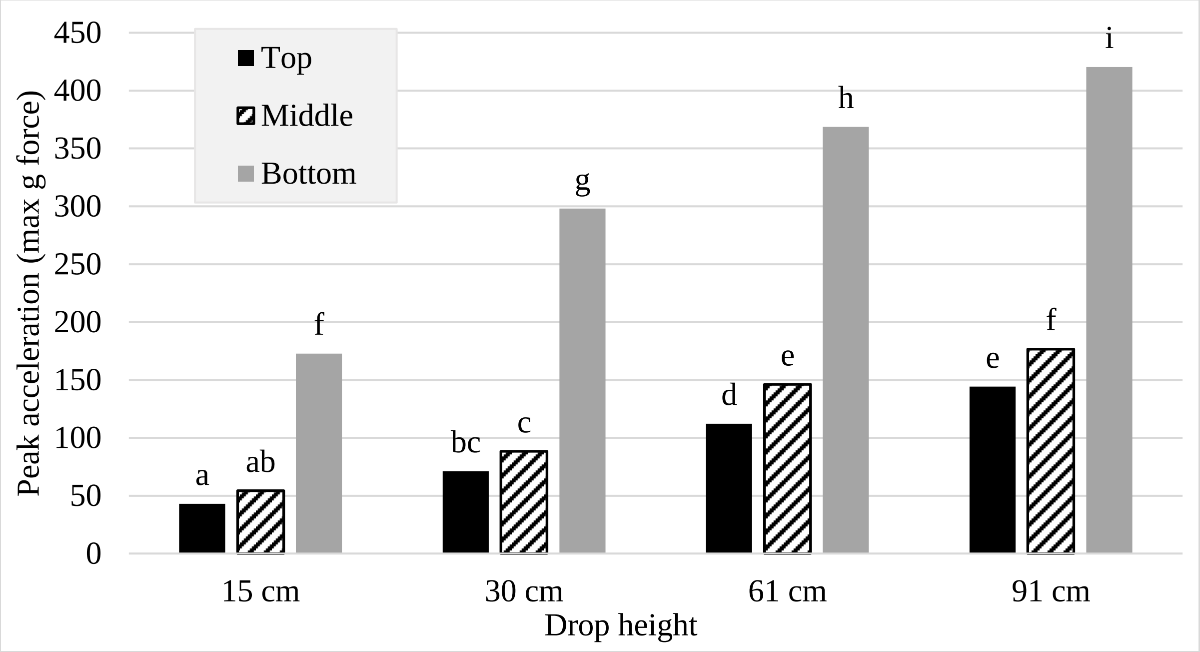

Figure 5-6. Peak acceleration of the impact recording device (IRD) as influenced by drop height (15, 30, 61, 91 cm) and placement within the box (top, middle, bottom). Values followed by the same letter are not significantly different (α<0.05).

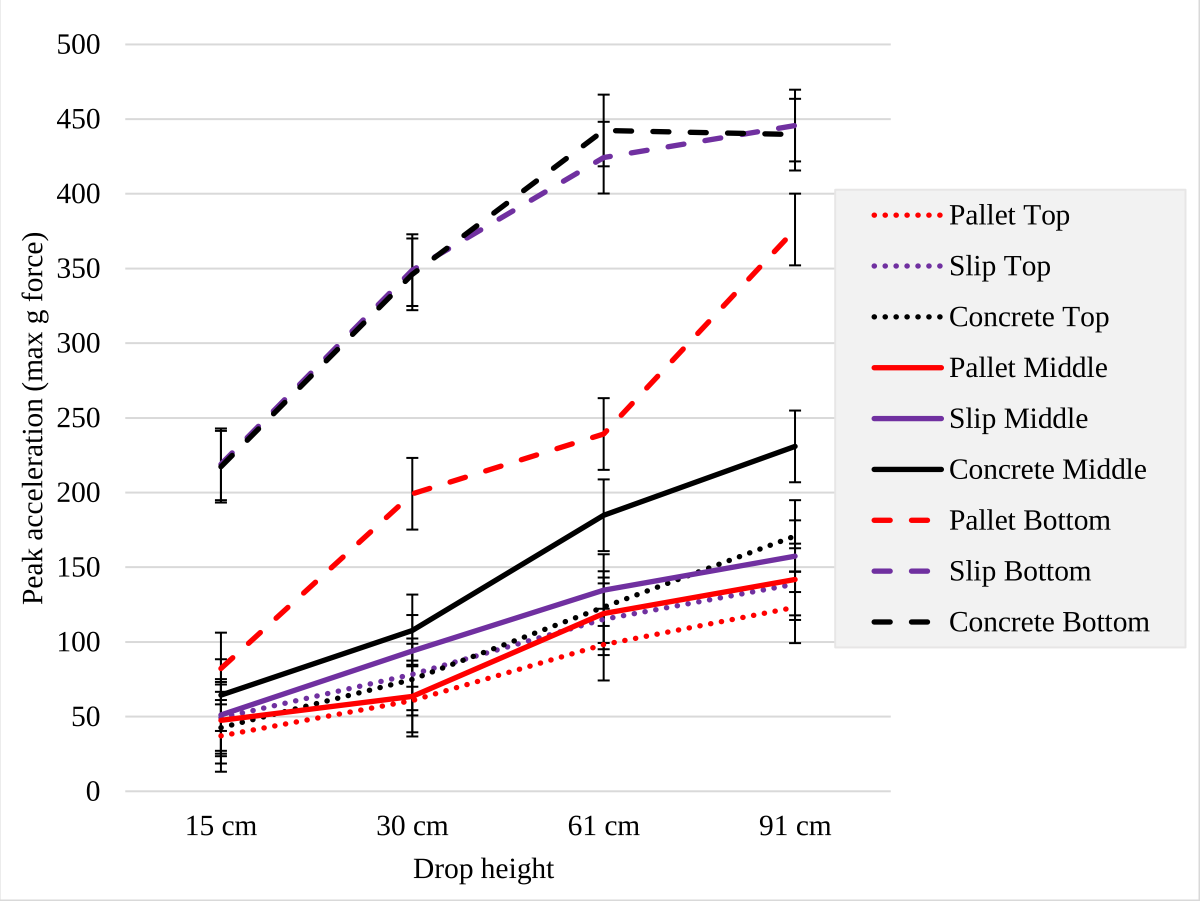

Figure 5-7. Peak acceleration as measured by an impact recording device (IRD; mean values ± SE) influenced by drop height (15, 30, 61, 91 cm), impact surface (wooden pallet, plastic slip, concrete floor), and placement within the box (top, middle, bottom).

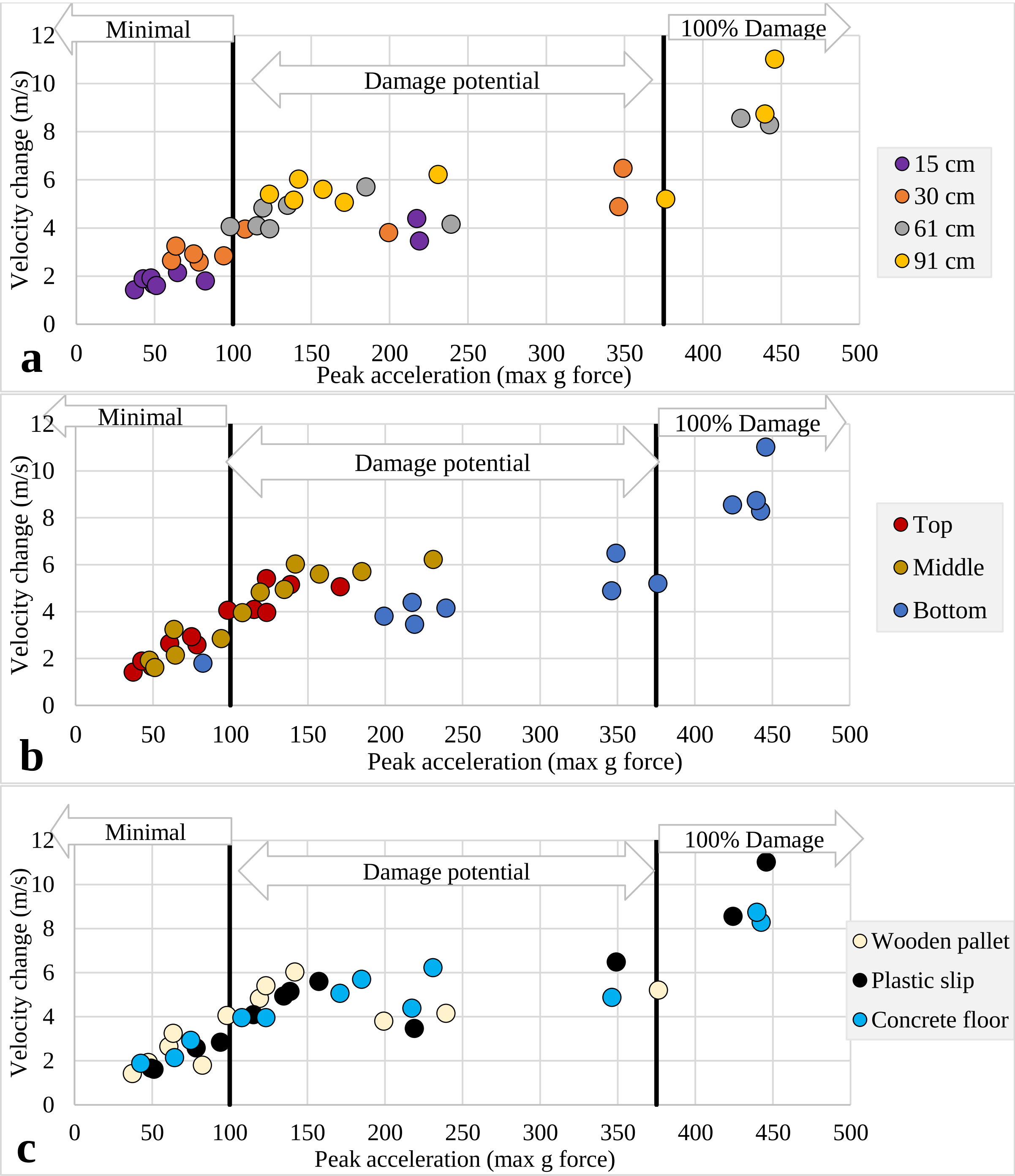

Figure 5-8. Peak acceleration and velocity change relationship measured by the impact recording device (IRD) and influenced by a) drop height, b) impact surface, and c) IRD location within the box. Data points from each graph are the same but colored differently to reflect the treatments. Hyde et al. (1992) determined bruise potential was low when peak acceleration was below 50g, high when above 100 g, and certain damage over 375 g. The major bruise potential zone was determined to be between 100 and 375 g (depicted by black vertical lines) and a high likelihood of physical damage.

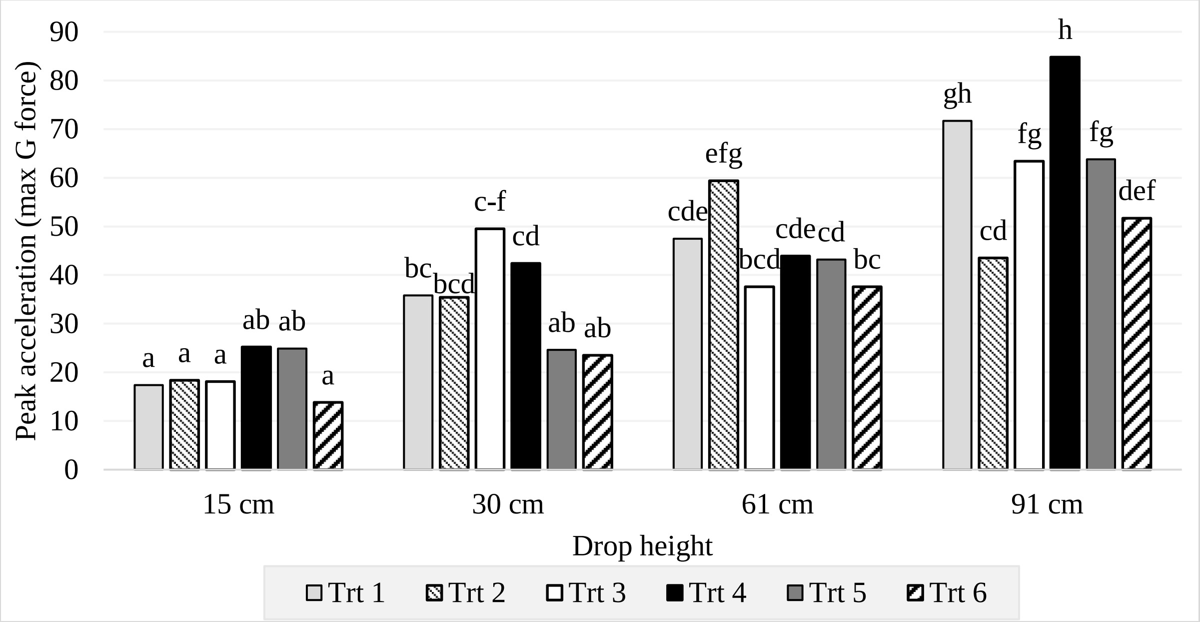

Figure 5-9. Peak acceleration as measured by an impact recording device (IRD) influenced by drop height (15, 30, 61, 91 cm), and treatment (IRD placement: top, middle or bottom of box) when boxes were dropped on other boxes (stationary or dropped box). Trt 1) Impact recording device (IRD) placed in the top of the dropped box, Trt 2) IRD placed in the middle of the dropped box; Trt 3) IRD placed in the bottom of dropped box, Trt 4) IRD placed in the top of the stationary box, Trt 5) IRD placed in the middle of the stationary box, Trt 6) IRD placed in the bottom of the stationary box. Values followed by the same letter are not significantly different (α<0.05) for each graph.

Chapter 6: Conclusions: Economic Implications of Blackspot and Shatter Bruise

As agriculture has developed to meet the demand of growing populations, countries have collaborated to ensure an abundant and safe food supply. The United States, one of the major players in global agriculture, has a government agency, the United States Department of Agriculture (USDA), that has jurisdiction over food safety regulations. Along with food safety, quality standards have been created to help promote healthy diets to decrease health issues in the United States (USDA 2019). Poor quality of fruits and vegetables equates to less consumption; therefore, standards take into consideration consumers' expectations and perceptions, which include high quality, dependability, and affordability (Savov and Kouzmanov 2009). Collectively growers, suppliers, distributors, retailers, and federal and state governments work to ensure expectations are met. Meeting quality expectations is economically and agronomically important for the potato industry, especially since potatoes are the most sold fresh vegetable in the United States (Karst 2019). Unfortunately, quality degradation can arise during post-harvest handling and product movement. Agronomic inputs and management are aligned to grow quality potatoes to have minimal physical damage (bruises), decay, and other defects, but incorrect handling throughout post-harvest operations can lead to sub-optimal quality when inspected at various points in the farm to customer process. Quality assessment, informally or formally, is done periodically throughout the entire post-harvest chain (Figure 6-1). Fresh market retailers are the final quality assurance that consumer expectations of raw potatoes are met.

Suppliers are packing facilities that prepare potatoes supplied from growers for the fresh market and then transport potatoes to their customer, the retailer. Preparation steps include sorting, inspecting, washing, packaging, and shipping potatoes to retailer distribution facilities or directly to the retailer. Each shipment must comply with USDA standards as being in suitable condition prior to leaving the supplier (USDA 2020a). Additionally, the retailer can specify that their in-house tolerances also be included in inspections. Retailer buyers conduct quality assurance inspections for each shipment of potatoes at distribution centers. Inspections are done internally following modified USDA quality inspection standards and additional USDA inspections can be requested. Inspection at this point in the post-harvest chain is to ensure quality degradation did not occur during transit from the supplier to retailer and provide proof of quality if any disputes arise (USDA 2020a). USDA standards for fresh market potato quality include grade, which is often a U.S. No. 1 or 2 grade (USDA 2011). These grade standards incorporate quality factors such as firmness, cleanness, shape, skin quality, and defect tolerance allowances. Defects can be internal or external and can arise from physical, physiological, or disease-related issues. Grade designation is dependent upon the level of defects and the tolerance levels specified by the USDA standards. Tolerance for the majority of defect categories ranges from 5 to 10% of total weight or surface area of the examined tuber or sample (USDA 2012). The defect is quantified by removing the defective area of the tuber and calculating the percentage of the removed area relative to the total weight of the tuber. Surface area quantification includes measuring the surface area the defect encompasses and calculating the percentage of defective area relative to the total surface area of the tuber. Measurement tools are often used to help estimate these areas. Certain defects, like soft rot or wet breakdown, have a lower tolerance. The allowable tolerance for these defects is only 1% presence within a sample by weight (USDA 2012). This lower tolerance would mean out of a 45 kg sample (which would be 1% of a 45,360-pound shipment), only 0.45 kg of potatoes with soft rot or wet breakdown presence would cause the shipment to exceed the tolerance level.

When defects exceed the allowable tolerance percentage(s), the entirety of the billed shipment can be rejected by the retail buyer's quality assurance personnel (USDA 2020a). Rejected shipments become logistically difficult to handle and economically damaging. Conversations with major suppliers and retailers provided the following insights on the logistics involved once a shipment is rejected. It is the responsibility of the supplier to remove the rejected shipment unless it has been at a distribution center longer than a determined amount of time, often five days. If the shipment is there longer than this timeframe it becomes the retailer's responsibility to dispose of the shipment. Once responsibility has been established, the rejected shipment needs to be removed and potentially replaced. The rejected lot can be sent to a packing facility to be repacked to meet the quality tolerances or be sold elsewhere. This process incurs additional costs and losses, but some value and return from the lot can be salvaged. In another option, the rejected shipment must be completely disposed. Disposal methods include either transporting to a local animal farm for feed, composting facility, donating to local food banks, or burial in a landfill. Disposal at a landfill is often a last resort because it increases food waste, shipment profits are completely lost, and additional costs are incurred from disposal fees. After the rejected shipment is removed from the retailer distribution center, the quantity of potatoes may be replaced with a different shipment to meet contract requirements between retailer and supplier. Sometimes these new shipments will not be accepted at the same quantity as the initial shipment, creating another loss in sales for the supplier. Transportation to remove and replace the rejected shipment incurs many costs. Additional trucking, fuel for hauling, and personnel to negotiate logistics and coordination of rejected shipments are extra costs and time the supplier must incur.

If a shipment passes inspection but is below the desired industry quality standards, the shipment is accepted but the supplier can receive a downgrade notice. This type of notice causes the supplier indirect issues. The retailer notes the frequency of downgrade notices and can use that information when negotiating future contracts with the supplier.

When a supplier receives rejection or downgrade notices from the retailer inspection, it is imperative to understand what defects resulted in the notice and if changes can be made to lessen the problem in the future. The University of Idaho, in collaboration with a major retailer, compiled rejection and downgrade notices from Idaho potato shipments to the retailer's distribution centers during the 2018 and 2019 crop years (August to following July) to use as a case study, which provided a comprehensive overview of the quality-related issues that caused shipment rejections. Determining the primary reason(s) for rejections can be difficult since defects can be classified under multiple categories. For example, shatter bruise could be the reason a shipment was rejected, but shatter bruise can fall under multiple categories such as cuts, mechanical damage, skin checks, air cracks, and/or clipped ends. To help in categorizing and simplifying the basis for rejections, the University of Idaho collapsed the defects noted on inspection rejection notices into 14 different categories which were modified from the USDA standards. Table 6-1 describes these categories.

The case study dataset consisted of 706 notices over the two years. In 2018 there was a total of 243 rejections (66%) and the remaining 125 notices were downgrades. In 2019, the percentage of the number of rejections was slightly lower (54%; 183 rejection notices) and the remaining 155 were downgrade notices. The average percentage of rejection notices over the two years was 60% and the remaining 40% were downgrades. Approximately 72% of the rejection notices compiled over the two years were associated with shipments of russet cultivars and the other 28% was a compilation of red, yellows or specialty cultivars (15%) and organic potatoes (13%).

A shipment can contain multiple cases of potatoes, but a shipment is determined by how it is billed to the retailer (USDA 2020a). For example, one shipment could include 800 cases of packaged potatoes because all were collectively billed together. Each shipment is made up of 50-pound cases (box or bale; imperial units are used in this discussion to align with industry units). Each case can include packaged potatoes ranging from 3 pounds to 50 pounds with the majority (62%) being 5-pound poly bags (10 bags of 5-pounds per case). To establish a rejection rate specific to the 5-pound bag cases, rejected cases were compared to all the 5-pound bag cases shipped from Idaho and received by the retailer during the same period. In 2018 the rejection rate for 5-pound bag cases was 3.0% accounting for 2.4 million pounds of rejected potatoes whereas, the rejection rate decreased in 2019 to 2.3% or 1.8 million pounds of potatoes. This would make the average annual rejection rate 2.7% over the 2-year period. In 2018, the top rejection categories were sunken discolored (20%), shatter bruise (16%), wet rot (15%), dry rot (11%), and external discoloration (8%). These rejections were similar in 2019 with slight variation: shatter bruise (18%), sunken discolored (17%), wet rot

(16%), blackspot bruise (15%), external discoloration (9%). Combining the two years, the top rejection categories were sunken discolored (18%), shatter bruise (15%), wet rot (16%), dry rot (11%) and blackspot bruise (11%) (Table 6-1). Rot and bruises are common rejection reasons for many fresh fruit and vegetable products and are considered some of the main quality defects and concerns throughout these industries (Terry et al. 2011).

It was evident that the top rejection categories were related to impact injury, but the extent of that relationship needed further examination. Shatter bruise and blackspot bruise were defined as directly related to physical impact injury (bruise), while wet rot, sunken discolored, and dry rot were defined as indirectly related to bruise. The remaining nine categories were determined to not be related to bruise. Directly related to bruise was defined as defects listed in the USDA inspection handbook that used the terms bruise, mechanical damage, or poor handling conditions in the defect definition (USDA 2012). Indirect relation to bruise was defined as defects that were the potential result of a physical impact as defined in the inspection handbook (USDA, 2012). For example, shatter bruise creates entry points for the Fusarium pathogen meaning Fusarium dry rot is indirectly related to bruise (Tiwari et al. 2020; Singh et al. 2021). Establishing an indirect relation to bruise had limitations for wet rot and sunken discolored. Wet rot can be caused by multiple factors. Some wet rot infections are related to shatter bruise injuries, whereas others may not, and therefore difficult to assign accurate estimates to the percentage of wet rot solely related to shatter bruise. Flattened or depressed areas (categorized under pressure bruise) can be misdiagnosed as sunken discolored in inspections. Pressure bruise is a separate type of bruise that may or may not occur from impacts but occurs in stored potatoes. Pressure bruise results in a flattened area on the tuber, which in this case study, was not categorized as relating to impact injury. The sunken discolored percentage may be skewed because the category encompasses multiple and varying defects. Any rejection that did not specify a relation to physical impact injuries was denoted as not related to bruise. In 2018, 23% of all rejections were classified as directly related to bruise, 46% were classified as indirectly related to bruise and 31% were not related. In 2019, the relation to impact injuries was slightly different with 33% classified as directly related to bruise, 45% classified as indirectly related to bruise and 23% not related to bruise. Averaging the rejection notices over the two years, 28% classified as directly related to bruise, 45% classified as indirectly related to bruise and 27% not related to bruise. Combining the direct and indirect categories indicated that physical impact-related quality concerns were estimated to be 69% in 2018 and 78% of all rejection reasons in 2019, averaging 73% over the two years in this dataset.

To provide economic estimates for what direct rejections have cost the US potato industry, the assumption was made that the United States retailer rejection rate is comparable to the Idaho rate in the single major retailer dataset (2.7%). Using this rejection rate, the proportion of rejections related directly or indirectly to bruise, we calculated that approximately 2.0% of all U.S fresh shipments were rejected due to impact related injuries (2.7% x 73% = 1.97%). The average value of fresh market potatoes in the United States in 2018 and 2019 was $1.24 billion dollars each year (USDA 2020b). This would lead to an estimate that the value of rejections in the fresh market due to a physical impact quality issue is $24.8 million dollars per year ($1.24 billion x 2% =$24.8 million). This estimated rejection rate and associated value of rejections does not account for additional costs incurred from handling logistics (as described above) once a shipment is rejected. There was a 26% reduction in volume (3.1% in 2018 vs 2.3% in 2019) of rejections from 2018 to 2019 that could be partially contributed to directed bruise mitigation education and research. If the industry follows the trajectory of reducing rejections by 25% per year, this could equate to a $6.2 million dollar savings of rejection losses each year. Using better bruise detection programs, investing in new handling equipment, and identifying cultivars more resistant to bruise-related defects, are all ways the industry could invest in bruise reduction programs to recoup some of these losses.

When fresh market potatoes arrive at the retailer end point for inspection, the potatoes have already gone through an extensive grading process to meet USDA standards. Potatoes that did not meet quality standards were graded out throughout earlier stages in the potato supply chain process (Figure 6-1) and delivered to an alternative market. The United Kingdom, who has similar standards of quality to the United States (Storey 2007), estimated 29 to 45% of the potatoes grown do not reach the retailer (Terry et al. 2011). Most product that is graded out throughout the fresh market chain goes to an alternative market, like dehydrated potato facilities or animal feed facilities, who partially rely on these losses for their product (Bolotova et al. 2008). Since impact-related injuries were identified as the most important contributor to the losses in the fresh market potato industry, the applied research in this thesis strived to examine ways to lower blackspot and shatter bruise throughout the whole potato chain.

Research outlined in Chapter Two examined how time in storage and location of impact on a tuber contributes to bruise susceptibility. Bruises inflicted on potatoes handled during the first two steps of the post-harvest operation (harvester and loading into storage; Figure 6-1) do not drastically change during storage. Blackspot bruises that develop after the initial impact at harvest will remain at a similar severity throughout long-term storage. Sub-sampling early in the storage season will therefore provide a reasonable estimate of the blackspot and shatter bruise level that will be seen through the rest of the storage season. Sampling for bruise susceptibility (as determined by impacting tubers in a consistent manner each month in storage) indicated blackspot bruise susceptibility increased slightly and shatter bruise susceptibility decreased throughout the storage season. These fluctuations occurred primarily between early and late storage, whereas in between, the bulk of the storage season, susceptibility was consistent for both types of bruises. One implication of these results is that potatoes with a high level of bruise at harvest may require extra care during subsequent handling out of storage and through the rest of the chain since those potatoes may continue to have a high level of susceptibility to impact damage and bruise. The results in Chapter Two also reinforced the notion that the shoulder and stem end of a tuber have higher blackspot bruise susceptibility, whereas the bud end and face are more susceptible to shatter bruise. When examining bruise levels of tuber samples in commercial operations, if blackspot bruise is seen on the bud end or shatter on the stem end, bruise susceptibility and handling conditions are extreme, and modifications need to be made. Susceptibility differences between the various locations on the tuber also provided justification for future research to examine the biochemical, mechanical and physical differences between the locations, especially relating to the face and shoulder of the tubers.

The research studies in Chapter Three examined how quickly one can observe blackspot bruise development following an impact. It was found that up to 70% of all blackspot bruise was visible within four hours. This new data would allow for more rapid assessment during harvesting operations than the previously suggested 24-to-48-hour window, potentially saving millions of pounds of potatoes exposed to impact damage. For example, assume within 24-hour day potatoes are being harvested at the same volume per hour. If samples are evaluated at hour four and high bruise levels are detected, 84% of the remaining crop in that 24-hour window have yet to be harvested. A modern harvesting operation in Idaho uses multiple pieces of harvesting equipment and often harvest between eight and 16 rows at one given time or between 8.4 and 16.8 acres per hour. This equates to 200 to 400 acres per 24-hour period. The average yield in Idaho for 2019 was 42,500 pounds per acre (USDA 2020b). Using a four-hour bruise evaluation window and assuming making proper mechanical adjustments to equipment would reduce exposure to bruise damage, then the quality of 7 to 14 million pounds of potatoes could be improved in the remaining 24-hour harvest period.

Chapter Four results highlighted impact force as a major contributing factor in cultivar susceptibility to blackspot and shatter bruise injury. An accurate way to test potatoes for bruise susceptibility is to use a consistent impact device and injure potatoes at different impact forces. The easiest method to alter impact force is by changing the drop height of the device. Most bruise susceptibility tests only use one impact force, which can provide misleading information about how a cultivar will respond to both minor and major physical impacts. The studies showed that to reduce the risk of blackspot bruise for Clearwater Russet and Dakota Russet potatoes, you cannot rely solely on reducing impact forces in handling operations because both cultivars are sensitive to even small impact forces. Other bruise mitigation tools, such as appropriate pulp temperatures at handling, may be more critical to integrate into bruise management programs for those specific cultivars. For Russet Burbank, Teton Russet, Umatilla Russet, and Ranger Russet, reducing impact forces could be a very beneficial management tool since bruise susceptibility decreased as the impact height decreased.

Chapter Five explored how losses could be minimized during fresh packing operations after potatoes are packaged for shipping. Potatoes are most commonly packaged in bulk 50-pound boxes or within 50-pound bales that hold 5 or 10-pound poly bagged potatoes. Once packaged, these potatoes are stacked on a pallet or plastic slip. Issues arise when the packaged potatoes are improperly handled as they are loaded and stacked. This handling could cause bruises to potatoes within the packaged box or bale at the final stage before they are transported to distribution centers. This study used an impact recording device to provide information on the peak acceleration (g-force) potatoes experienced at different drop heights in boxes or bales of potatoes. The risk of bruise is minimized as boxes and bales are dropped from lower heights and cushioned with the use of wooden pallets; although, the potatoes at most risk for bruise are in the bottom of the boxes. Increased cushion for the bottom stack of potatoes during palletization in fresh pack facilities could lower the risk of bruise. Cushioning the surface under stacked boxes and lowering drop heights would be excellent practices to further integrate into fresh packing facilities to lower bruise in packaged potatoes.

This project provides information for the industry to make informed decisions about how to manage for bruise at harvest, in storage, unloading, and in fresh pack and processing facilities. Providing research-based education and information is the first step in mitigating bruise. Integrating these practices in each step of the potato supply chain is continuous and evolving. Future research and education efforts should include an economic analysis of the logistics associated with impact-related injuries throughout the entire post-harvest chain to further explain the cost associated with blackspot and shatter bruise in the industry. Examining areas within a fresh packing shed with an impact recording device could further explain the risks associated with quality in a fresh packing facility and cushioned plastic slips could provide an alternative to wooden pallets. Bruise susceptibility research on new cultivars should incorporate impact on all surfaces of the tuber as well as incorporate different pulp temperatures to further explain why cultivars respond to different impact heights.

There is an economic benefit to reducing bruises throughout the post-harvest chain rather than losing profits because of bruise-related rejections. It is estimated that 29 to 45% of potatoes designated for the fresh market do not reach the retailer (Terry et al. 2011). Lowering the potential loss to the lower end of the range (29%) by utilizing some of the bruise management recommendations could be worth an estimated $198 million dollars of potential revenue for fresh market potatoes in the United States (16% x $1.24 billion average value of fresh market potatoes). This thesis focused on applied approaches to issues surrounding blackspot and shatter bruise in the potato industry and provided insight toward future basic and applied research, which can help improve handling practices and reduce the risk of bruise in the future.

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Tables

Table 6-1. University of Idaho's compilation of defects in rejection notices in relation to bruise and the percentage of rejections associated with that category during the 2018 and 2019 crop year.[1]

University of Idaho category description	Relationship to bruise	2018 rejections (%)	2019 rejections (%)	Average rejections (%)[2]
Blackspot Bruise	Direct	7	15	11
Black Spot				
Internal Black Spot				
Bruises (Quality)				
Bruises (Condition)				
Shatter Bruise	Direct	16	18	17
Cuts				
Mechanical Damage				
Skin Checks				
Air Cracks				
Cracking				
Cuts/Clipped Ends				
Surface Cracks				
Dry Rot	Indirect	11	12	11
Dry Rot				
Dry Rot (External)				
Dry Rot (Internal)				
Sunken Discolored	Indirect	20	17	18
Sunken Discolored				
Sunken Discolored Areas				
Sunken Discolored Sticky Areas				
Sunken Discolored Areas with Underlying Flesh Discolored				
Wet Rot	Indirect	15	16	16
Soft Rot				
Wet Breakdown				
Decay				
Soft Rot (External)				
Soft Rot (Internal)				
Soft and Decay				
Wet Breakdown (External)				
Dehydration Damage	Not Related	1	0	0
Firmness				
Shriveling				
External Damage	Not Related	1	2	1
Growth Cracks				
Insect Damage				

Second Growth				
Grub Damage				
Rodent/Bird Damage				
External Discoloration…………………………	Not Related	8	9	8
Surface Discoloration				
External Surface Discoloration				
Rhizoctonia (Black Scurf)				
Elephant Hide				
Rough Raised Netting				
Russet Scab				
Silver Scurf				
Greening………………………………………..	Not Related	1	0	0
Greening				
Internal Discoloration………………………….	Not Related	3	4	4
Brown Center				
Chilling Injury				
Internal Brown Spot				
Brown Spot				
Stem End Browning				
Light Brown Discoloration				
Hollow Heart or Hollow Heart with Discoloration				
Net Necrosis				
Lenticels………………………………………..	Not Related	6	3	5
Lenticels				
Enlarged Lenticels				
Packaging………………………………………	Not Related	3	1	2
Underweight				
Wrong Item				
Slightly Dirty				
Cleanliness				
Product Damaged				
Pressure Bruise……………………………...	Not Related	5	3	4
Flattened or Depressed Areas				
Sprouts…………………………………………	Not Related	3	1	2
Sprouts				

[1] Rejection notices only include notices that were considered rejected. These percentages do not include downgraded notices.

[2] Rejection percentage is based on number of notices and was not weighted by total volume of shipments to the retailer each year. The average rejection is the mean of the two years.

Figures

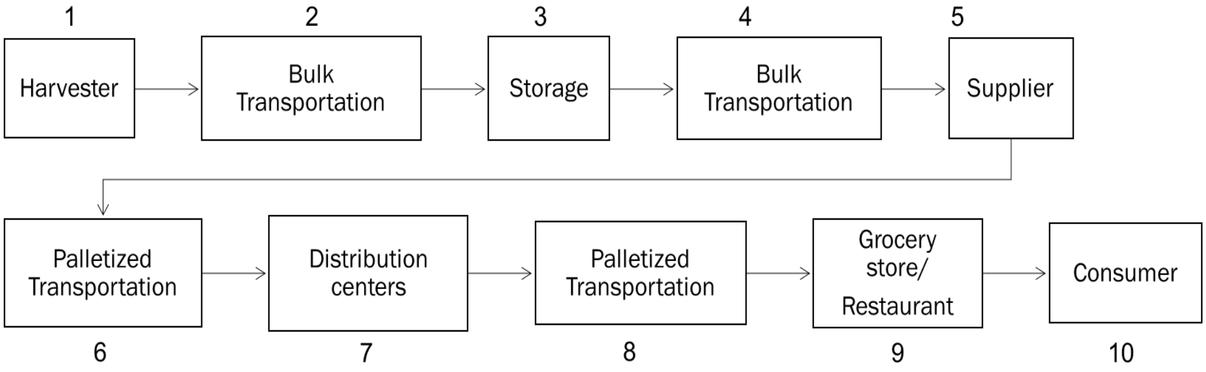

Figure 6-1. Schematic of the potato post-harvest handling operation chain. Each time potatoes are moved there is potential for impact injury and bruise. Depending on operation, steps three and four may not be involved.