EVALUATING VINE-KILL HARVESTED POTATOES TO DETERMINE EFFECTS OF HARVEST WAIT PERIODS ON DAMAGE RESISTANCE AND TO DETECT SURFACE AND SUBSURFACE DAMAGE WITH SPECTRAL MEASUREMENT

By

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To my parents, Brenda and Jeffrey; and everyone that helped me make it to this point in my academic career

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LIST OF ABBREVIATIONS

a	acceleration
B	B coefficient
CCD	Charge Couple Device
CI	Confidence interval
CVTEST	Cross Validation
d	Distance
F	Impacting load
g	gravitational force
h	Drop height
h2	Rebound height
I	Intensity
m	Mass
NIRS	Near infrared spectroscopy
p	Sample proportion
PCR	Principal components regression
PDI	Potato damage index
PLS	Partial least squares
PRESS	Predicted Residual Sum of Squares
PTFE	Polytetrafluoroethylene
r	Correlation coefficient
R^2	Coefficient of determination
RH	Relative Humidity
RMSD	Root mean square difference
RPD	ratio of prediction to deviation

RSS	Residual sum of squares
SDBI	Surface damage and bruising index
SMLR	Stepwise multiple linear regression
SEC	Standard error of calibration
SEP	Standard error of prediction
UV	Ultraviolet
v	Velocity
VNIS	Visible and Near-Infrared Spectroscopy
W	Weight

Abstract of Thesis Presented to the Graduate School of the
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Any force exerted on a potato tuber during harvesting and packaging may result in mechanical damage. Mechanical damage and disease are major problems in the harvesting and movement of potatoes from the field to consumer. Being able to quickly identify and remove damaged potatoes during post-harvest handling could reduce storage costs for potatoes which never make it to market. Excessive deterioration in market quality of potatoes from mechanical damage and defects cut into the profits of the producers and shippers. Vine-kill is a practice which involves killing the upper portions of plants by spraying with herbicides or cutting the vines. After the upper portion of the plant has been killed, the potato tubers are left in the soil undergoes skin set which involves the periderm thickening and becoming more damage resistant. This thickening of skin also helps to prevent storage diseases and shrinkage due to water loss. However, leaving tubers in the ground can increase their exposure to brown rot, insects and other deteriorating conditions. The two cultivars used for this study were 'Fabula' and 'Red La Soda'.

A study was carried out to simulate potato handling in a repeatable manner to investigate the damage thresholds of each cultivar at different points from harvest through packing. Potato

tubers were collected 7 days before vine-kill, the day before vine-kill and then 7, 14 and 21 days after vine-kill. A set of potatoes from each cultivar was run along the same portion of a packing line each harvest to access skinning resistance, while the remaining tubers were used for drop tests. Drop tests were performed 1 day and 7 days after harvest; then stored to allow internal bruising and shatter to develop before being assessed. Tubers were dropped from the following heights; 30 cm, 30 cm double, 60 cm, 60 cm double, and 90 cm. Analysis of 'Fabula' data showed a clear decrease in skinning and drop damage between pre-vine-kill and only 7 days of skin set; while 'Red La Soda' maintained consistently low skinning damage, but during drop testing there was a remarkable decrease in damage development after 7 days of skin set.

A study was also carried out in order to collect spectral data of vine-killed potatoes for the purpose of grading and sorting both cultivars. Spectral measurements were made on undamaged potatoes after harvest, after simulating mechanical damage and then following 7 days of storage at 20°C (68°F) in order to allow internal and external damage to develop. Spectral data were also collected for tubers showing greening, brown rot, shatter, growth cracking, sunscald and insect damage. After collecting data for the wavelength range between 200-2500 nm for moisture content, it was decided to concentrate on the sensing range between 360-800 nm due to water having less effect on reflectance measurement and equipment pricing of spectrometers for packing houses. Analysis showed that undamaged reflectance properties of each tuber cultivar were altered in predictable ways depending on which defect was present. The change to the spectral reflectance caused by defects was found to be statistically significant using PLS and SMLR analysis; which would allow the potential of detection and elimination of damaged tubers on a packing line.

CHAPTER 1
LITERATURE REVIEW

1.1 Introduction

The United States is the fourth largest potato producing country in the world with a yearly production of around 20 million metric tons, while the yearly production of potatoes is approximately 325 million metric tons for the entire world. The United States, however, is the leader in metric tons produced per hectare with production averaging around 44.6 metric tons/hectare compared to the world's average of 16.8 metric tons/hectare (FAO, 2008). The average Florida potato yield is 48 metric tons/hectare, with a marketable yield of 41.5 metric tons/hectare (Hutchinson and Gergela, 2007). This means there is an average of 9% loss of product during packaging and storage. Only about one third of potatoes grown in the United States are consumed fresh. Around 60 percent of annual U.S. potato output is processed into frozen products (such as frozen fries and wedges), chips, dried products and starch production, while 6 percent is re-used as seed potato for future production. Each American eats more than 54 kg of potatoes every year (FAO, 2008). While Florida is not one of the top ten potato producing states in the United States by volume, producing only 2% of the annual supply in the U.S.; it ranked 7th for the high-value winter and early spring potato production in which Florida produces one-third of the winter/early spring crop supply. Florida's potato industry generates more than $160 million in annual revenues for the state due to its profitable production window (USDA, 2008).

Mechanical damage in agricultural production is a major cause of low grade quality (USDA, 2008). The mechanization of agricultural processes in the U.S. has favored the development of increased mechanical damage on produce. Mechanical damage that occurs on

potatoes includes skinning, internal blackspot, pressure bruising and shatter. Skinning is an injury in which the tuber periderm is removed by friction. Internal blackspot is a discoloration of the tissue below the periderm due to an impact on the potato tuber surface damaging internal cells; these damaged cells then generate the black pigment called melanin. A pressure bruise is a depression of the tuber surface that occurs due to a constant external pressure at the point of contact between adjacent tubers or storage surfaces. Shatter is the result of a mechanical impact that causes internal or external splitting (cracking) of the tuber. Mechanical damage diminishes the income of potato farmers by reducing the quality and quantity of potatoes that are harvested from their fields. The elimination of produce that has been mechanically damaged during harvest and reduction of mechanical damage caused during processing would help improve the quality of product and increase profits by eliminating the storage costs associated with storing these damaged potatoes. Potatoes that have been stressed from mechanical damage or disease also reduce the income of farmers by increasing the load requirements of cooling and moisture maintenance of storage areas.

The above ground portion of potato plants is killed prior to harvest in order to promote tuber periderm development (i.e., “skin set”). Potato tubers that have been allowed to undergo skin set after vine-kill tend to have a much lower chance of developing mechanical damage. But the extended time spent underground exposes the tubers to other major causes of lowered grade quality such as soft rot and other decays due to various pathogens, black heart, freezing, and insect damage. These damaging defects have a more likely chance of occurring the longer a tuber is left in the ground before and after vine-kill.

1.2 The Potato

Potatoes (*Solanum tuberosum*) belong to the "nightshade" family (Solanaceae) of flowering plants, and share its genus Solanum with at least a thousand other species, including tomatoes and eggplants. These herbaceous annuals grow up to 100 cm tall and produce a tuber, which is referred to as the potato, that is so rich in starch that it ranks as the world's fourth most important food crop behind maize, wheat and rice (FAO, 2008). As a potato plant grows, sugars are produced in the leaves that are transported to and then stored in its underground stems as starch. These stems are separate unique organs, distinct from the roots. As these stems thicken at their distal ends from storing starch, they begin to form tubers (potatoes). The number of tubers present in a fully matured potato plant depends on the availability of nutrients and moisture in the soil. The potato that is grown today is a single domesticated botanical species of potato that contains just a fragment of the genetic diversity developed by farmers in the central Andes Mountains region over the course of millennia; that contains thousands of varieties with diverse sizes, shapes, skin or flesh color and other sensory characteristics.. The potato varieties that are grown worldwide and known as "the potato" are all from one domesticated species out of two hundred species of wild potatoes, which are found in the Americas. There are seven recognized potato species and 5,000 varieties grown in the Andes (FAO, 2008). The end of a growing season is generally accompanied by cold weather, which triggers the plant's leaves and stems to die down to soil level and its tubers to detach from their stolons (FAO, 2008). Once the plant begins to naturally die back at the end of the season, the tubers undergo a process of skin set which allows them to toughen up for the harsh cold weather so that they can later re-grow into new plants when environmental conditions improve.

1.3 Harvesting After Vine-kill

Harvesting after vine-kill is a practice that involves killing the upper portions of the potato plants by either spraying them with herbicides, by mechanically cutting or a combination of both methods; the potato tubers are then left in the soil to allow their skins to set (Hutchinson and Stall, 2007). Skin set helps prevent storage diseases, skinning and shrinkage due to water loss. However, the longer tubers are left in the ground the more exposure they receive from the fungal incrustation called black scurf, decays such as brown rot, damage from insects eating portions of the tuber, and rot caused by heavy rains and other harmful environmental conditions. Vine-kill is also performed in order to prevent spread of virus diseases by aphid infestations, to kill and to prevent spreading of late blight spores on foliage, to prevent spreading and reduce late blight tuber rot infection, to control tuber size by terminating above ground plant growth in order to take advantage of early market demand, and to improve removal of vine growth that interferes with harvest (WPC, 2011). After the vines are killed, sunscald and greening (i.e., chlorophyll synthesis in the tuber epidermis) can affect tubers that are not sufficiently covered with soil and are no longer protected by vegetative cover. To allow for less problematic harvesting, potato vines are currently killed 2 to 3 weeks before the potatoes are scheduled to be harvested. Production scale then determines the harvesting method that will be used; potato tubers can be harvested using a spading fork, a plough or commercial harvesters that unearth the entire plant and remove the soil from the tubers (FAO, 2008).

Tubers harvested from living vines are more likely to be severely skinned and bruised during harvest; their heavy green foliage may also interfere with harvest machinery (Olson and Simonne, 2006). Immature tubers from living or very recently killed vines are typically more susceptible to the skinning and mechanical injury that can take place during harvest and sorting.

These immature tubers also tend to have higher sugar and lower starch concentrations than mature tubers. According to Hutchinson and Stall (2007), the maturity of tubers at harvest is an important aspect in the production quality of Florida fresh market potatoes. Tubers that have reached suitable maturity have a better level of skin set, enhanced bruising resistance and improved storage life. Vine-killing before harvest has an additional benefit wherein it improves tuber release from potato vines. In its area of origin and most of the major commercial growing regions in temperate areas, tubers are able to naturally mature as the potato plant senesces due to changes in weather; however, improved production methods and farming in areas without distinct seasonal changes allow potato vines to remain healthy and green longer into the growing season preventing tubers from maturing and beginning the skin set process. This is the reason why tuber maturation is artificially induced by killing the potato vines at ground level.

Harvesting is usually done 14 to 21 days after vine-kill in order to allow the periderm to set and to reduce the amount of skinning and scuffing. Senescent vines and vines in poor condition due to disease or other factors do not have to be killed as long before harvest as vigorous vines in order for the periderm to be set (Olson and Simonne, 2006). Due to the natural process by which tubers begin to mature when harsh conditions begin to kill off plant foliage above the surface in order to survive until favorable conditions return.

1.3.1 Mechanical Vine-Killing

Mechanical vine-killing generally refers to the destruction of potato vines by disintegration of the vines by beating, chopping or burning. Mechanical vine-killing is often used to terminate tuber growth, to ease harvesting by destroying vine structure, or to take advantage of an early market (Murphy, 1968). Flail mowing and rolling are the two of the most popularly used

methods of mechanical vine-kill for potato harvesting. It is suggested that these methods be used 14 to 21 days preceding the planned harvest period to insure ample time for tubers maturation and skin set. Since revolving flails or blades can damage tubers and create air flow that can expose tubers by moving loose soil, care should be taken when using mechanical methods to avoid disturbing the soil so that tubers close to the surface are not exposed, leading to greening, sunscald or mechanical damaged (Hutchinson and Stall, 2007). Burning potato vines is a method of destroying vines that utilizes a series of burners directed to obtain a uniform heat or flame coverage on the vines. Complete incineration often requires more than one flaming and can be more expensive than chemical methods. Burning of the vines also destroys organic residues and nitrogen needed for soil maintenance (Murphy, 1968). Other methods of mechanical vine-killing include pulling and steaming.

1.3.2 Chemical Vine-Killing

The most common method of vine-kill tends to be chemical desiccation. This method involves the application of agricultural grade chemicals to kill the potato vines over a varying number of days; depending on the type used it can take 1 day and a single application or 2-3 weeks and several applications to achieve full vine-kill. According to Hutchinson and Stall (2007), chemical vine desiccants should not be applied during cool and damp or hot and dry weather in order to avoid stem end discoloration from rapid vine-killing. Vine-kill can also be improved for actively growing plants by splitting application of the chemical desiccant; this can also help skin set development. Split application can only be implemented if the chemical's label permits for it; this is performed by an application of desiccant at less than full rate followed by a second application several days later (Hutchinson and Stall, 2007). Chemical vine-kill is usually

used to terminate vine growth over time, to prevent oversized tubers, to harden tuber skins, and kill late blight spore and prevent spread of tuber rot (Murphy, 1968).

1.3.3 Combined Methods

Combining mechanical and chemical methods to perform vine-kill can improve the efficiency of vine desiccation and speed up the tuber maturation process of skin set (WPC, 2011). The use of a roller in order to bend and partially kill vines; while spraying chemical desiccant results in improved foliage and stem coverage and more efficient chemical vine-kill. Combining the methods allows for fewer applications of chemicals in order to achieve a faster complete vine-kill. Another advantage of combining vine rolling with chemical application is that it may close cracks in the potato row that results in a reduction of incidences of tuber greening and sunscald after vine desiccation by preventing tuber contact with sunlight (Hutchinson and Stall, 2007). For a very rapid vine-kill, flail vine shredders can be combined with a chemical application after a short wait period to allow debris to fall off of the remaining vine before application. This flailing reduces the chemical desiccant applications required for completing vine-kill and results in a very fast rate of vine-kill which allows the vine-kill procedure to be timed closer to the harvest date and thus extends the length of time available for the tubers to bulk up and mature physiologically (WPC, 2011).

1.4 Packaging and Storage

During commercial production, the packing line process begins when trucks bring tubers from the field and dump freshly harvested potatoes onto the packing line in-feed elevator, which takes the fresh potatoes through an initial wash area utilizing overheard watering and brushes to move the potatoes forward (Fig. 1-1). Once the potatoes are washed, they go through a sorting

area where potatoes with defects, injuries and/or diseases are removed. The potatoes that make it past the sort table are then taken by elevator to an accumulator before entering the primary wash area. In the primary wash area, potatoes are moved forward by brushes again while being watered from above before entering a sponge roller area that takes them through the sizer. The sizer separates potatoes by using slowly increasing gaps to drop different sized potatoes onto divided sections. Once the potatoes have passed the sizer, they enter the drying area where most of the surface moisture from the two washes is removed before entering the grading table where the final inspection of potatoes is performed before proceeding to the packing area where potatoes are put into their storage containers.

Newly harvested tubers are living tissue, making proper storage essential. When storing potatoes, facilities need to be designed to keep the potatoes alive and healthy, and must be able to slow the natural tuber senescence which includes the conversion of starch to sugar (WPC, 2011). It is important to store potatoes in a dark, well ventilated environment with an optimum relative humidity of 90% at a temperature of 3.9 to 10°C (39 to 50°F) depending on the variety. These storage conditions are intended to prevent greening and losses in weight and quality. Several distinct storage phases exist which will ideally allow potatoes to be stored up to 10 months (Calverley, 1998). Mathew and Hyde (1997) found that potato tubers which had been stored over 5 months rarely show any signs of blackspot bruising. The four main storage phases are curing, cooling, long-term storage and marketing. The best practice for each storage phase depends on tuber conditions, weather and projected use of the crop. New potatoes grown in Florida do not undergo the curing process because they are produced for the table stock market and sold shortly after harvest.

1.4.1 Pre-Harvest Period

Most storage problems begin in the field before harvest begins. Potatoes from healthy vines have been shown to be much more resistant to storage decay than those harvested from vines that had been weakened from physiological stress or diseases. Good storage practices and management can help maintain the tubers, but poor quality produce that has already been damaged will not improve during storage. The storage facility should be prepared well in advance of harvest in order to allow time for proper cleaning and disinfection.

1.4.2 Cooling Period

The greatest amount of water loss (shrink) occurs after harvest is complete and potato tubers are placed into storage. The potato pile temperature is initially maintained in the range of 4.4 to 12.8°C (40 to 55°F) depending on pile conditions and ultimate use. Tubers destined to become chips are generally stored at 10 to 12.8°C (50 to 55°F), while french fries are stored at 7.2 to 8.9°C (45 to 48°F), and finally fresh market and seed potatoes are maintained near 4.4°C (40°F) (Bohl and Johnson, 2010). Afterward the potatoes should be warmed to 10°C (50°F) to prevent bruising damage before being removed from storage or need be cooled to the long-term storage temperature at a rate of 2 to 3°C (4 to 5°F) per week, since rapid cooling of potatoes has a tendency to cause coloration problems in processed potatoes (Bohl and Johnson, 2010).

The ventilation used during cooling is determined by the cooling requirements, the need for fresh air to remove the products of respiration and for maintaining relative humidity (Brook et al., 1995). Ventilating is mainly done to maintain the pile at the desired temperature, but ventilation may be required more frequently if there is excess condensation on the tuber surfaces.

An excess of surface moisture can encourage soft rot, so continuous ventilation is often recommended when condensation is present.

1.4.3 Long-term Storage Period

The main objective for potatoes destined for long-term storage is to maintain a consistent ideal environment for the entire storage period to maintain tuber quality while facilitating marketing. Recommended storage temperatures are determined by condition, as well as, intended use. Sugar levels in potato tubers can increase during storage due to conversion from starch, which is favored at lower temperatures, Soluble sugar content greater than 0.5% is very undesirable for potatoes intended for processing, especially frying, because the sugars are caramelized at cooking temperatures. It is generally accepted that no more than a 1°C (1.8°F) difference should be maintained between the top and bottom of the pile (Brook et al., 1995). Storage temperatures can be maintained more uniformly if continuous ventilation is used; especially during periods when outdoor temperatures are considerable lower. A relative humidity above 95% is recommended for long-term storage.

1.4.4 Marketing period

Reconditioning after long-term storage is a procedure that improves the color of processed potatoes. This is accomplished by increasing storage temperatures to 10 to 18°C (50 to 64°F) for 2 to 4 weeks before marketing. These higher temperatures increase tuber respiration rates, which reduces the sugar amount of soluble sugars that may have accumulated in the tubers during storage by using those sugars as substrate. The reduced sugar levels improve chip and fry coloration when cooked. These higher storage temperatures also increase shrinkage, possibility

of rot and may break the dormancy of sprouting in tubers. Thus it is recommended that processing occur within 1 month of reconditioning (Brook et al., 1995).

1.5 Potato Quality Factors

A potato tuber's size, shape, and physical appearance, as well as the presence or absence of diseases, defects and damage all contribute to potato quality. Pathogens affect all parts of the potato plant, and disease can develop at any time during the potato production and storage season. These pathogens can cause extreme reductions in yield and quality of a potato harvest, individually and as complexes (Stevenson et al., 2001). Potato tubers can also display a number of defects and disorders that are not the result of disease or insects. Some of these external and internal defects and disorders are caused by mechanical damage. External tuber damage can reduce the marketability due to unfavorable reactions by consumers and also cause reductions in processing quality and storability. Internal tuber damage usually goes undetected until after tubers are cut and inspected unless it is extensive enough to reach the surface of the tuber. This type of damage can also result in severe reductions in crop quality, marketability and storability.

1.5.1 Mechanical Damage of Potatoes

Any mechanical force exerted on a potato tuber during harvesting and packaging may result in mechanical damage. Damage to potato tubers due to mechanical forces is among the most important causes of loss of quality reported throughout the world (Peters, 1996). This mechanical damage is a major problem in the harvesting and movement of potatoes from the field to consumer. Excessive deterioration in market quality of potatoes caused by mechanical damage can cut into the profits of the producers and shippers (Nylund et al., 1955). Mechanical damage costs the potato industry by increasing storage losses due to shrinkage and disease,

increasing labor costs for trimming and inspecting, increasing the cost of raw product through greater trim losses, lowering the quality of final product, increasing the incidence of disease and decreasing shelf life, and finally by reducing the appeal of fresh potatoes to wholesale and retail customers (Thornton and Bohl, 1998). Fresh market potato consumer standards are usually associated with visual characteristics such as shape, firmness and exterior appearance being free from defects and disorders. Mechanical damage can occur in several different forms including minor skin abrasions (skinning), external shatter, internal shatter, cuts and blackspot bruising. These main types of damage and their causes are listed (Table 1-1).

Mechanical damage is one of the most important causes of loss of potato quality reported throughout the world. In a U.S. study by Preston and Glynn (1995), it was reported that for the total potato production in the United States valued at $2 billion, losses of at least $125 million occurred between potato fields and the consumer. Skinning is the most common type of mechanical damage and if severe enough can result in USDA grade losses for the product (Table 1-2). While slightly skinned tubers are able to heal with proper storage, these tubers can still result in increased shrinkage rates from water loss and from tubers using stored energy to repair the damage. Early and later blight infection can sometimes occur on these skinned tubers that have lost their protective periderm (Stevenson et al., 2001). Other mechanical damage, such as bruising and shatter, can also result in a loss of grade when present at moderate to serious levels that detract from the edible or marketing quality. Removal of injured tissue from bruised and shattered tubers causes losses of 5 to 10 percent of the total weight of the potato (USDA, 2008).

1.5.1.1 Causes of mechanical damage

Mechanical damage to potato tubers can occur at any of several stages of production, especially during harvesting and sorting operations; which vary by the variety of potato being processed. Blahovec (2005) analyzed the effects of different cultivation conditions on the mechanical damage of ‘Agria’ tubers using pendulum impacts and found that impact properties only slightly depended on cultivation regime; implying that a varieties damage resistance could impact mechanical damage more than conditions during the growing season. In one American investigation, it was reported that 70% of the damage done to potato tubers occurred at harvest and the remaining 30% occurred during transport and storage (Peters, 1996). Thornton and Bohl (1998) reported that there are four factors that have a major influence on the amount and severity of mechanical damage: 1) soil conditions, 2) tuber condition, 3) equipment maintenance, adjustment, operation and modification and 4) magnitude of tuber impact. Chiputula et al. (2009) found five types of mechanical damage while researching ‘Fabula’ and ‘Yukon Gold’ during harvesting and packaging operations; the damage found were skinning, external shatter, cuts, internal shatter and blackspot bruising, that were mainly caused by harvesting operations.

Skinning can often be the result of rough handling of immature potato tubers, which causes the skin to be easily scuffed or rubbed off. Blackspot bruising occurs when a potato tuber undergoes a significant impact against a solid object, damaging cells in the tissue just beneath the skin without actually breaking the skin; that results in the damaged tissue developing a black pigment over the course of 24 to 48 hours called melanin. Shatter bruising occurs when impacts cause cracks or splits in the potato tuber skin and/or extending into the underlying tissue (Thornton and Bohl, 1998).

Skinning and cutting are often caused by mechanical harvesters as they dig the tubers out of the soil. Dumping and tumbling of potatoes on mechanical equipment during harvesting and unloading onto packaging lines can also lead to skinning and cutting, as well as, external shatter, internal shatter, and blackspot bruising. Nylund et al. (1955) investigated the causes of mechanical damage during harvesting and handling operations and found that diggers, trucks, unloading and bin to shipping bag operations all contribute to mechanical damage which can lower the U.S. grade number from 1 to 2 or less. Mechanical damage can be linked to drop height and potato tuber size due to the increase in impact force that is created by increasing either of those factors. Thornton and Bohl (1998) reported that research has shown the greater the drop height, the larger the force, and the more likely that a bruise will occur, especially when drops are greater than 6 inches and the tuber is supported underneath by a hard metal roller or plate.

1.5.1.2 Mechanical damage prevention

Prevention of mechanical damage often begins before planting with good plowing etiquette to avoid the formation of clods in wet, heavy textured soil and the removal of rocks, so that when it comes time to harvest there is less debris to come in contact with potato tubers on harvester conveyors (Thornton and Bohl, 1998). The next step is to plant in time to allow potato plants to reach desired maturity before performing vine-kill and harvesting at the end of the season. Vine-killing is a vital step in mechanical damage prevention; allowing skin set to toughen tuber skins and allowing tubers to reach proper maturity increases resistance to skinning and shatter bruising. Thornton and Bohl (1998) reports that providing adequate fertilization of potassium and calcium enhances the ability of potato tubers to heal wounds and also reduces susceptibility to blackspot bruising.

At the end of the season is it very important to try and harvest under as near ideal temperature and soil moisture conditions as possible, in order to maximize the number of bruise-free potato tubers acquired (Thornton and Bohl, 1998). When potato tubers become dehydrated and limp they are more susceptible to blackspot bruising, while being over hydrated and crisp cause's potato tubers to shatter bruise more often. If soil moisture contents drop below 50 percent after vine-kill, tubers become more likely to dehydrate excessively and irrigation should be used to supplement a lack of rainfall. Generally, as tuber temperature increases, less bruising occurs. However, it is considered ideal to harvest and handle potato tubers when temperatures are between 10° C and 15.6° C (50° F and 60° F) because temperatures above 18° C (65° F) promote storage decay (Thornton and Bohl, 1998).

Dry, sandy soil can separate from potato tubers too quickly as they move over the harvester conveyors, which need to carry soil to the end of the secondary chains to operate properly. An under loaded conveyor increases tuber irritation and can lead to higher levels of mechanical damage. Thornton and Bohl (1998) suggested that light irrigation should be applied to soil before potato harvest in order to partially moisten the soil and overcome problems with excess soil separation on conveyors. Furthermore, if irrigation is not an option, it was recommended that the forward speed of harvesters should be increased in order to increase the load of tubers and soil on primary and secondary conveyors. On the other hand, it was suggested that when soil is too moist at harvest, the forward speed should be decreased in order to reduce the load of tubers on the primary and secondary conveyors to offset an increase in bed agitation of potato tubers.

1.5.2 Environmental Physiological Defects of Potatoes

The potato is a host to many pathogenic organisms that include bacteria, fungi, viruses, viroids, nematodes, and phytoplasmas; however, fungi, bacteria and viruses are the dominant causes of potato diseases (Bohl and Johnson, 2010). These pathogens can cause extreme reductions in yield and quality of a potato harvest, individually and as complexes. Adverse environmental conditions and certain agronomic factors can also negatively affect the health of the potato plant and quality of harvest (Stevenson et al., 2001). Some of the common defects that occur in Florida potato fields and their causes are listed (Table 1-3). Controlling pathogens and preventing environmentally caused defects is central to successful, quality potato production.

Many pathogens enter potato tubers during harvest when tuber periderms are damaged by mechanical harvesting. These pathogens go unnoticed until they begin to decay the affected tubers during storage. Other pathogens are transmitted by insects serving as the mechanical vector or their feeding providing an entry -point for pathogen invasion into the tuber flesh (Bohl and Johnson, 2010). The general practices to prevent and control diseases suggested by Bohl and Johnson (2010) include: 1) Handling seed tubers sanitarily, 2) following a regular and rigorous sanitation program, 3) irrigating uniformly and adequately but not excessively, 4) controlling aphids, leafhoppers, and nematodes, 5) harvesting and handling tubers gently, 6) never harvesting when tuber temperatures are below 7 °C (45 °F) or above 30 °C (86 °F) and 7) providing an environment conductive to wound healing, followed by proper temperature, humidity, and aeration during storage. Defects caused by environmental conditions cannot be controlled by growers, however, proper management can help promote uniform growth and minimize the impact of environmental stresses. This includes establishing a uniform stand, monitoring soil moisture, irrigating in a timely manner, using soil tests to help fertilize for

reasonable yield goals, and using proper storage conditions to reduce losses (Bohl and Johnson, 2010).

1.6 Reflectance Measurement

Visible and near-infrared spectroscopy (VNIS) is a nondestructive method of product evaluation that uses the phenomena associated with visible light and near-infrared reflectance and transmission, the instrumentation, laboratory analysis, and data-processing to detect differences in the physical and compositional status of the measured samples. When a material is exposed to visible light, it may be selectively reflected, absorbed or transmitted; rendering wavelength dependence to the emergent radiation that is perceived as color. Similarly, near-infrared radiation may be selectively reflected, absorbed or transmitted by a sample. This phenomenon is well known, providing a basis for structural study and quantitative analysis using transmission spectroscopic techniques (Dahm and Dahm, 2001). According to Yee and Gimel'farb (1999), there are four advantages that have contributed to the popularity of near infrared spectroscopy (NIRS): 1) the fact that samples take very little preparation and a spectrum can be acquired quickly. 2) The process is non-destructive and the same sample can be retained for other analytical procedures or returned to the population. 3) Analysis can be performed to determine more than one constituent from a single scan or spectrum. 4) There is no dependence on highly skilled personnel to operate the instrumentation required to perform scans.

1.6.1 Effect of Water on Spectral Characteristics

It is well known that water strongly affects the reflectance spectra of sample materials at various wavelengths. Yee and Gimel'farb (1999) reported that spectral analysis is widely used for moisture determination in food, but different chemical constituents of produces pose

problems for accurate measurement of moisture due to shifts of peak spectral responses and changes in peak spectral responses in the absorption bands. Water is the most important substance necessary for plant growth and water content varies extensively in potatoes. Potato tubers have been reported by the potato industry to contain huge amounts of water (73.8% to 81%), according to Souci et al. (2000). While experimenting with determining potato tuber water content using NIR diffuse reflection methods, Elbatawi et al. (2008) found water content levels from as low as 40% to as high as 85% with average water contents around 81.7%.

Water is an excellent absorber of infrared energy at several wavelengths, which can strongly affect reflectance spectra of potatoes. Carter (1991) discovered that water content had primary and secondary effects on leaf spectral reflectance. These primary effects resulted from the radiative properties of water, while the secondary effects were those that could not be explained solely by these properties. Generally as the water content of the leaves decreases, reflectance increased throughout the entire wavelength range measured (400-2500 nm) with the greatest sensitivity to water content being between 1,300 and 2,500 nm, especially near the water absorption bands at 1,450, 1,940, and 2,500 nm. Additionally, Carter (1991) also determined that a secondary effect occurred between 400-720 nm that resulted in decreased absorption by pigments. Yee and Gimel'farb (1999) stated that the fundamental absorption of water occurs at approximately 3,840 nm of the infrared region with the first, second and third overtone at approximately one half, one third and one fourth of the fundamental (1920, 1280 and 960 nm, respectively), but in reality the overtones will not follow this exact relationship due to losses and inefficiencies occurring between molecular interactions. By performing a full spectral analysis of the suspected water absorbing bands Yee and Gimel'farb (1999) was able to find strong evidence for 5 maximum wavelengths between 0.7 - 2.5 μm at 0.76, 0.97, 1.19, 1.45, and 1.94 μm.

Muir et al. (1999) determined that water loss from the tissue in and around an area could be attributed to pathogens such as common scab, dry rot, skin spot and gangrene; but it could not be linked to the somewhat wetter rots associated with bacterial soft rot or blight because the tissue will not dry out to the same extent. Fassio and Cozzolino (2004) used a NIRS spectrum between 1100 and 2500 nm in order to predict the chemical composition of sunflowers along with their water content; concluding that re-calibration may be necessary for moisture and oil over different harvests due to climatic or agronomic conditions. Bull (1991) suggested that if the reflectance at the reference wavelength is sensitive to the moisture content of the sample, the calibration will only be linear over a relatively small range of moisture contents. This may be inconvenient in a practical instrument. In this case, it is preferable to choose closely matched absorption and reference wavelengths for which the reflectance is relatively insensitive to moisture content.

1.6.2 Application of Spectroscopy in Food Analysis

Nondestructive detection such as, photoelectric detection, electromagnetic characteristics analysis, NIRS, X-ray analysis, computer vision and so forth, have been used more frequently in food and agricultural industries for product inspection and evaluation in order to provide reliably objective assessment at a rapid rate with an economic price tag (Jin et al,. 2009). After determining a wide range of parameters present in food products spectroscopic techniques began to receive worldwide attention. Spectroscopy's main advantages are its speed, little to no sample preparation, and the absence of chemical use. However, well-designed calibration processes must be performed in order to allow for the best model predictions of specific parameters of interest in the desired food product (Singh et al., 2005). Porteus et al. (1981) reports that the interaction of only 3 causative agencies can account almost entirely for the range of spectral types recorded

from tubers suffering from a number of defects through the application of the statistical techniques of factor analysis and discriminant analysis. Using the information from only a few wavelengths, individual defects can be detected instrumentally with about 80%. The detection of some diseases can even be determined before their presence causes effects that are visible to the eye. With further instrumentation it would be possible to construct a device that could recognize a number of defects in tubers with an acceptably low failure rate.

Numerous nondestructive sensing techniques have been studied for predicting firmness, sugar or soluble solids, and other quality attributes of apples and other fresh agricultural products. Light-based sensing technologies, especially NIRS, offer great potential for predicting internal quality of fresh fruits and has the potential to nondestructively measure multiple quality attributes of agricultural products simultaneously (Lu and Ariana, 2003 and Kang et al., 2004). The nondestructive technology NIRS has received significant consideration as a means for detection of fruit quality. The rapid nondestructive technology NIRS is fairly easy to use with online and offline applications. NIRS also has the potential to simultaneously evaluate numerous quality traits of apples. In order to be adapted for online sorting applications a sensing system must be able to obtain spectral information from a product rapidly. Advances in charge coupled device (CCD) technology allows for rapid measurements using a spectrophotometer that obtains spectral information from all wavelengths of a spectral range in the visible and short NIR region from around 400 up to 1100 nm simultaneously (Lu and Ariana, 2002).

Porteous and Muir (1986) used light ranging in wavelength from 650 to 1680 nm to assess seed potatoes versus human assessors. Machines used to estimate the extent of disease on tubers were more reliable than human assessors; due to the estimates varying widely between different assessors and between repeated evaluations of tubers by the same assessors. The optical

methods investigated provide a basis for the design of quality grading machines which could compete with inspectors in accuracy of sorting. Liew et al. (2001) developed a method of using fiber optic spectroscopy to detect green and red fluorescent proteins in vitro and in vivo in order to select appropriate markers for identifying genetically engineered plants as a step towards improving public perception of bio-safety over the current methods of screening plants based on antibiotic resistance. Muir et al. (1999) reported using optical spectral reflectance in the visible to near infrared range (400 nm to 2000 nm) to take measurements of 11 different varieties of potatoes grown in Scotland. These data were used to compare reflectance properties of disease-free tubers with the properties of tubers exhibiting several types of artificially introduced disease defects. Using the first 3 eigen-vectors they were able to account for 96.1% of the variance in measurements. The varieties selected to represent the range of skin and flesh colors were considered in groups defined by their combination of brown, pink, yellow or white skin with yellow or white flesh. Lefebvre et al. (1995) reported using a combination of grey scale, flourometry and infrared techniques to detect sprouting of potato tubers. Flourometry was used to emit an excitation wavelength at 488 nm and a band pass filter around the emission value of 680 nm for successfully detection of sprouting.

Internal discoloration is one of the major defects of potatoes. One of the internal discolorations in potato characterized by a discolored cavity in the center of potato tubers is called Hollow heart. Hollow heart previously had not been detectable without cutting. Kang et al. (2004) set out to detect Hollow heart using a robust VIS/NIR transmittance measurement technique for determining specific gravity or dry matter in potato tubers nondestructively with 87% accuracy. They used both quantitative and qualitative modeling methods were employed to

develop models for predicting and classifying internal quality in potatoes based on specific gravity.

Clark et al. (2003) used a clinical MRI system to preselect 240 apples to establish a uniform range of disorder from 0 to 100%. The sample apples containing the internal browning disorder ‘brown heart’ showed pronounced spectral changes observed in the range 700 to 900 nm as the percentage of browned tissue increased. The visible and near-infrared spectra of bruised and intact spots on Jonagold apples were acquired from 400 to 1700 nm with spectrophotometers and by using PLS analysis a total classification accuracy of more than 90% could be achieved for detecting bruises on Jonagold apples (Xing et al., 2005).

Hyperspectral imaging can be used to distinguish variations between the normal or abnormal parts of a sample using the spectra of image pixels. The technology uses the pixels from an image to provide a spectrum using a combination of imaging, spectrometric, and radiometric techniques. Multispectral image analysis is a faster technique based on a discrete spectral analysis at a few wavelengths as opposed to the continuous spectral analysis performed by the hyperspectral imaging technology. Mehl et al. (2002) used these techniques to create a 100% accurate linear discriminant model to separate normal and abnormal conditions of Gala apples, while their models for Red Delicious and Golden Delicious apples showed limited classification accuracy with results below 70% for normal and abnormal apples and Golden Delicious showing results of 85% accuracy.

Lu (2003) used an imaging spectroscopy system to successfully acquire scattering images from apple fruit over the spectral region between 500 nm and 1000 nm. Imaging spectroscopy goes beyond conventional imaging and spectroscopy to acquire both spectral and spatial

information from an object simultaneously. As a result, it greatly expands the capability to identify or detect some subtle or minor features in an object. Equally successful studies have been performed on a wide range of defects for many fruits and vegetables. Therefore, previous research results indicate that there should potentially be no limitations for application if spectroscopic techniques for the evaluation of other varieties of potatoes and defects.

1.6.3 Alternative Food Analysis: Machine Vision

Machine vision systems are widely applied in automatic sorting, since they can give consistent and objective evaluations compared to human inspection. Defect detection by machine vision systems is strongly dependent on the light intensity difference between sound and bruised surfaces making bi-colored products difficult to screen (Xing et al., 2005). Computer vision technology has the advantages of real-time, objectivity, low cost and high precision; which can effectively detect the external features of potatoes. Jin et al. (2009) reported collected results for correct classification rate of defects, correct recognition rate of defects and correct inspection rate of potatoes based on Fixed Intensity Interception (FII), which operates under a controlled lighting condition and setting a CCD camera in an automatic shooting mode, that were 92.1%, 91.4% and 100%, respectively. The results of defect detection on yellow-skinned potatoes showed this approach was fast, valid and convenient. Davenel et al. (1988) developed and tested on-line, a system for automatic detection of surface defects on Golden Delicious apples on a conveyor system used for automatic color grading. While the fruit was rolling, a solid-state camera took four pictures, and so was able to view most of the surface. The tests on line showed that 69% of the fruit were correctly graded, but 26% were classified immediately above or below the right grade.

Grading operations on packing lines are predominantly performed by trained human inspectors who inspect potatoes by looking or feeling for certain quality characteristic. Human inspectors have a few disadvantages, which include inconsistency, a shortage of labor, and slow grading speeds that can't keep up with huge production volumes. This is why it is necessary to convert grading over to automation in order to provide a more consistent product quality and handle larger volumes of materials. The appropriate hardware and software for produce handling and grading is required to incorporate machine vision and automation into a completely automated inspection station for packing lines Potato motion can adversely affect shape analysis and contribute any errors in classification (Heinemann et al., 1996). Tao et al. (1995) trained a machine vision system to distinguish between good and greened potatoes and yellow and green 'Golden Delicious' apples. The method created proved highly effective for color evaluation and image processing by using the HSI (Hue, Saturation and Intensity) color system. An accuracy of over 90% in the inspection of potatoes and apples was achieved by applying multivariate discriminant techniques to the features that were represented with hue histograms.

1.7 Simulation of Mechanical Damage

There are different degrees of mechanical damage that can be sustained at any stage of production from pre-harvest operations, harvesting and subsequent handling operations when the product is graded, packed and transported for market or storage at a new location (Calverley, 1998). This damage includes anything from skinning and bruising to deep cuts; if mechanical injury is serious enough, the product may be rejected during grading resulting in losses. Any damage to the tuber skin can also lead to physiological deterioration and entry of decay pathogens which can result in losses later on. Impact testing can be used to evaluate the potential for damage to occur under different conditions. Impact testing is the evaluation of an object's

ability to resist high-rate loading of energy absorbed in a collision with a test object at high velocity (Instron, 2011).

1.7.1 Damage Resistance of New Potatoes

Impact resistance is one of the most important biological properties of agricultural products. Bajema and Hyde (1998) reported that the two components of impact sensitivity are: bruise threshold and bruise resistance.

- Bruise threshold of a given tuber mass and impact surface is the drop height at which bruising starts to develop.
- Bruise resistance of a given tuber mass is the bruise energy per unit of bruise volume; while the inverse is the bruise size for a given bruising drop height.

Bruising is influenced by tuber mass, impact height, slowdown distance, and impact deceleration. Impacts on a hard surface result in much higher impact deceleration and short slowdown distance, while impacts on soft or padded surfaces result in lower peak impact deceleration and lowered slowdown distances (Bajema and Hyde, 1998).

It was determined by Mathew and Hyde (1997) that the type of impact damage that occurred in potato tubers and the size of bruising damage were influenced by drop height. The percent of tuber samples that were damaged increased as the drop height increased for samples of 250 ± 30 g (8 to 10 oz.), but when the drop height increased beyond 200 mm (8 in.), the number of samples with blackspot bruising decreased and more critical types of tissue failure began to appear; at 450 mm (18 in.), blackspot damage occurrence dropped to zero. The mechanical damage of potato tubers can result in blackspot bruising when sufficient damage occurs that causes a mixing of substrate and an enzyme (tyrosine and polyphenol oxidase) that

results in the black discoloration, melanin. Discoloration of tissue can only occur if the substrate and/or the enzyme are present in adequate quantities.

1.7.2 Skinning Simulation

In order to determine the effects of changing conditions on the skinning of potato tubers, tubers need to be handled in a similar manner each time and repeatable experiments must be performed. Hall (1953) used a method of skinning that involved washing tubers before placing them in a skinning apparatus consisting of a garbage can lined with ½ in mesh hardware cloth. This can was then rotated for 3 minutes on rolls at about 10-11 revolutions per minute. Afterward each tuber sample was rated individually using a rating system of 1 (for least skinning) to 5 (for most skinning).

1.7.3 Impact Damage Simulation

When seeking to obtain the statistical bruise thresholds of fruits and vegetables; groups of uniform sized samples must be dropped from various known heights onto identical impact surfaces and the percent of samples in each group that show bruising must be noted (Bajema and Hyde, 1998). The biggest disadvantage related to the testing of falling samples is that heavier samples will impact with greater energy when dropped and samples must be weighed so their mass may be considered; according to the well-known formula, $F = ma$, where F = force, m = mass, and a = acceleration. Fluck and Ahmed (1973) suggested that impact velocities less than 250 mm/s should be considered slow loading since a drop height of only 3.2 mm results in an impact velocity of 250 mm/s. The equation for impact velocity is given by equation (1-1).

$$v_i = \sqrt{2gh} \tag{1-1}$$

where h is the travelled distance of a falling object and g is the gravitational force.

Impact velocities have historically been considered to range from 250 mm/s to as high as 40 m/s for agricultural products. Thus, most impacts occurring during handling of fruits and vegetables are in the fast loading-rate range; and since bruising is uncommon at less than 3.2 mm drop height, dynamic loading need not be considered in evaluating bruising.

Fluck and Ahmed (1973) found that the measured parameter, peak force, increased with increasing drop height and increasing mass that was dropped. This supports the hypothesis that peak force and resulting internal stresses are critical elements in the incidence of impact damage due to stress concentration at the tissue failure point. A large potato tuber dropped from the same height as a small tuber has more kinetic energy and will more likely sustain greater damage during handling even though smaller tubers typically have smaller radii of curvature. Tubers with small radii of curvature are also particularly prone to damage because impact forces are concentrated upon a smaller area of the tuber surface. In addition, cell size increases as potato tuber size increases. Larger cells tend to have thinner cell walls, resulting in possibly weaker tissue in larger specimens (Bajema and Hyde, 1998). The equation for impact force is given by equation (1-2).

$$F = \frac{1}{2}mv^2 \Big/ d \qquad (1\text{-}2)$$

Where m is the mass of the free falling potato tuber, d is the slowdown distance determined by the flex in potato flesh at impact and v is the impact velocity.

1.7.4 Detection and Evaluation of Mechanical Damage

Finding mechanical damage means finding the physiological responses of potato tissue to physical damage. Tuber tissue responds to damage by attempting to heal itself, which results in increased respiration and ethylene production at the site of injury. If the damage is sufficient enough to cause cellular disruption that mixes the substrate and enzyme involved in oxidation of phenolics (i.e., tyrosine and polyphenol oxidase), black discoloration develops due to melanin production (Mathew and Hyde, 1997). Bruise damage does not show up immediately after impact. Thornton and Bohl (1998) reported that blackspot bruising appears in damaged tissue over the course of 24 to 48 hours as tissue begins to progress from grey to black over time; this makes it difficult to determine how much damage was done or will develop at time of impact. Blahovec (2006) reported that blackspot bruising occurs more often when impacts involve tubers of greater size, poor hydration causing limpness, potassium deficiency, warmer harvest temperature, less significant drop heights and old or very mature tubers. Thornton and Bohl (1998) reported that shatter bruising occurs when impacts are great enough force to generate cracks or splits in the potato tuber skin and/or underlying tissue. Shatter bruising is more likely to result from impacts involving tubers of greater size, crisp texture (i.e., well-hydrated tissue), cooler harvest temperature, higher drop heights and immature tubers.

The decision making process involved in grading and packaging top quality potatoes is based heavily on product appearance, which requires reliance on human visual interpretation. The majority of the actions involved in this labor intensive task are highly repetitive and boring, with accurate grading depending greatly on the effectiveness and efficiency of human operators which Muir et al. (1999) reported can be as low as 8% and at best 60%. This makes detection and evaluation of mechanical damage using human graders difficult, particularly if the damage is

below the surface or still developing. This has led to efforts to develop special techniques or instrumentation to accurately and nondestructively detect and measure such damage. Some of the non-destructive methods for detecting and evaluating internal defects of fruits and vegetables include x-ray absorption devices, MRI, and spectral-based sensing.

1.7.4.1 Vine-kill wait period assessment

A popular damage assessment system created by Robertson (1970) is called the Potato Damage Index which requires that tuber be washed and dipped in a paracresol, a red stain that reveals wherever the surface of the tuber is damaged; the tubers are then examined and separated into four categories:

1. Undamaged- No staining;
2. Scuffed- Skin broken but no flesh damage;
3. Peeler- Flesh damage to a depth not greater than 1.5 mm;
4. Severe- Flesh damage deeper than 1.5 mm.

The potato damage index (PDI) is calculated as shown in equation (1-3):

$$PDI = \%\, scuffed + 3 \times \%\, peeler + 7 \times \%\, severe \qquad (1\text{-}3)$$

A newer index created by McGechan (1980), which accounts for both surface damage and internal bruising called the surface damage and bruising index (SDBI) is calculated as shown in equation (1-4):

$$SDBI = \%\, scuffed + 3 \times \%\, peeler + 5 \times \%\, bruised + 7 \times \%\, severe \qquad (1\text{-}4)$$

Many mechanical damage studies carried out on potatoes have involved varieties in growing areas that produce potatoes for storage; these storage varieties are usually not marketed

as fresh market ‘new’ potatoes. The reaction to impact force that potatoes display often depends on the variety, growing conditions and pre-harvest practices. Also, since new potatoes do not undergo the curing phase of storage used for wound healing; results from damage studies conducted using storage varieties cannot always be applied to the handling of new potatoes since potatoes react differently to impact forces after harvest and after curing. It is common practice for researchers to design their own scales for the experiments and evaluation methods for mechanical damage. Chiputula et al. (2009) tested two new potato varieties ‘Fabula’ and ‘Yukon Gold’ in order to determine mechanical damage threshold and harvesting and packing operation components which contribute significantly to mechanical damage. Results showed that components affected each variety to different degrees and the main form of mechanical damage wasn’t always the same. Research like this is rare; therefore there is a need to investigate mechanical damage with the different new potato varieties and handling systems used in Florida potato production.

1.7.4.2 Spectral measurement assessment

A primary interest of reflectance spectroscopy is the rapid and nondestructive assessment of certain aspects of a material. The objective is to accurately record the wavelength-dependent nature of absorption relative to a stable standard (Dahm and Dahm, 2001). According to the Beer-Lambert Law, the concentration of an absorber is directly proportional to the sample absorbance as shown in equation (1-5):

$$Absorbance = log_{10}(\frac{I_o}{I_t}) \qquad (1\text{-}5)$$

with I_0 being the intensity of the incident radiation and I_t the intensity of the transmitted radiation.

A calibration model is developed by using the NIR spectra and known analytical information in order to calculate the regression equation to create a model that can be used to predict future outcomes. Several parameters are evaluated to create a calibration model: factors, loadings, and scores. It is important to avoid under or over-fitting when choosing the number of factors to be used. The prediction model will be unreliable if an insufficient number of factors are used; since useful information may be left out of the model. However, more uncertainty will be included in the calibration set if too many factors are chosen, which can cause errors in prediction to occur. The number of factors used will generally be determined by using the minimum Predicted Residual Sum of Squares (PRESS) value associated with factors, in order to increase accuracy. Scores are used to check the sample homogeneity and possible clusters; while loadings are used to interpret how the variables are weighted in principal component space (Hatchell, 1999). Crowe and McNichol (1985) consider the critical step of any calibration the identification of a suitable set of four or five wavelengths where the combined changes in optical density correlate highly with the constituent of interest.

The successful prediction of defects or disease using VNIS is largely based on identification of significant wavelengths that will act as markers. This is one of the main issues of spectral-based sensing technology, because the success of a calibration model heavily depends on the selected wavelengths. Min et al. (2004) described correlation coefficient spectrum as the simplest method to determine important wavelengths between absorbance and the desired measurements. The correlation coefficient (r) lies between −1 and 1, with a value of 1 indicating that the two variables X and Y are directly related with one increasing with the other for a linear equation, while a value of −1 indicates data points lie on a line for which the variables Y and X are inversely related. No linear correlation exists between variables for data points which have a

value of 0. The variables X and Y are used to represent the wavelengths and damage for this project.

The initial introduction of derivatizing spectral data as a concept was introduced in the 1950s, when its many advantages for qualitative and quantification analysis were presented (Owen, 1995). A first-order derivative is the rate of change of absorbance with respect to wavelength, as shown by equation (1-6):

$$\frac{dA}{d\lambda} = f'(\lambda) \tag{1-6}$$

where a spectrum is expressed as absorbance, A, as a function of wavelength, λ.

The 1st derivative is a plot of equation 1-6 using the absorption envelope versus wavelength. Derivative spectral data can be produced by processing the spectrophotometer output. Using the derivative spectra would be beneficial because it can increase the detection sensitivity of minor spectral features and reduce the error caused by the overlap of the analytic spectral band by interfering bands of other species in the sample.

Partial least squares (PLS) regression in its simplest form is a linear model that specifies the relationship between a dependent variable Y (response), and a set of predictor variables X. PLS was initially introduced by Wold (1975) and has been heavily promoted in chemometrics literature and more recently, in other fields as well. Lingaerde and Christophersen (2000) referred to the PLS method as a linear model that estimates parameters when predictor variables are close to being collinear. PLS can be characterized in terms of the scaling (shrinkage or expansion) that occurs with each eigenvector of the predictor correlation matrix. Helland (2001) considered PLS to be a two-step method where the first step reduces the matrix dimensions (m

and n) which represent the values of the row and column; while the second step identifies latent structure models in the data matrix. PLS procedures work by extracting successive linear combinations of the predictors underlying the Y and X variables from Y'Y and X'X matrices, until ideally explaining response variation and predictor variation with minimized response prediction error; though the number of prediction functions can never exceed the minimum of the number of Y variables and X variables. In contrast to principal components regression (PCR), which extracts factors to explain as much predictor variables variation as possible without considering the response variables, the PLS method explains both the response and predictor variations by balancing the two objectives and seeking the factors that explain the variation (SAS, 2009).

According to Hatchell (1999), a model's validity must be tested. This can be done by separating a data set into two groups; one group is used for calibration and the second group is used for validation. Cross validation can be performed if there are not enough samples by leaving one sample out at a time and using the rest of the samples to build a calibration model and predicting the sample that was excluded. Cross validation has the advantage of excluding the prediction sample from the calibration model, unlike calibration with a full data set. In order to complete a PLS model the number of factors must be chosen using the PRESS statistic in PLS. The factors are chosen using cross validation, in which the data sets are divided into two or more groups. The model is fit to all groups except one; the capability of the model is then checked to predict responses for the group omitted. This is repeated for each group in order to measure the overall capability of a given form of the model. The PRESS statistic is based on the residuals generated by this process. The optimal number of factors for PRESS is generally obtained when factors are minimized with a smaller PRESS value indicates a better model prediction (Sundberg,

1999). Selecting the number of factors for which the absolute minimum PRESS exists is not always the best choice, since a lower number of factors may have a significantly close PRESS value. The CVTEST (Cross Validation) option in SAS PLS, which is a statistical comparison suggested by van der Voet (1994) can be used in order to perform a test on the significance of the PRESS values for each number of factors.

When interpreting PLS outputs Esbensen (2002) states that; X-loadings are used to signify common variations in the spectral data, while X-weights signify the fluctuations in the spectra that resemble the regression constituents. Thus, high X-loadings and X-weights are used in order to isolate important wavelengths. However, the main purpose of PLS regression is to build a linear model with the B coefficient taken from the traditional regression equation (1-7):

$$\mathrm{Y} = \mathrm{X} \cdot \mathrm{B} \tag{1-7}$$

with Y being *n* cases by *m* variables response matrix, X *n* cases by *p* variables predictor matrix, and B a *p* by *m* regression coefficient matrix.

The B coefficient provides a complete picture of the most significant wavelengths. Wavelengths with higher B values are able to provide better results for a calibration model, and are considered to be more significant wavelengths. The B coefficient is calculated using PLS loadings and weights as shown in equation (1-8):

$$B = w(p'w)^{-1}q' \tag{1-8}$$

with w being the X-weight, p the X-loading, and q the Y-weight.

The reliability of calibration models can be assessed by using the coefficient of determination (R^2) found comparing predicted damage concentration and true concentration,

standard error of calibration (SEC), standard error of prediction (SEP) which signifies the accuracy of the results, root mean square difference (RMSD) and ratio of prediction to deviation (RPD) as shown in ASTM (1997). The SEC, SEP, RMSD and RPD were of determined by the equations (1-9 through 1-12):

$$SEC\ (g \cdot kg^{-1}) = \sqrt{\frac{1}{n-p-1}\sum_{i=1}^{n} e_i^2} \tag{1-9}$$

$$SEP\ (g \cdot kg^{-1}) = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n} (e_i - \bar{e})^2} \tag{1-10}$$

$$RMSD\ (g \cdot kg^{-1}) = \sqrt{\frac{1}{n}\sum_{i=1}^{n} e_i^2} \tag{1-11}$$

$$RPD\ = \frac{SD}{SEP} \tag{1-12}$$

with n being the number of samples, p the number of independent variables in the calibration model, e_i the difference between actual N concentration and predicted N concentration in the ith sample, and $\bar{e}$ the mean value of e_i.

Stepwise multiple linear regression (SMLR) is a form of forward regression that aims to obtain a robust model using a minimum number of characterizing variables obtained from a large set of potentially useful variables that permits re-examination at every step of the variables incorporated into the model in previous steps (Yee and Gimel'farb, 1999). Each forward selection step, with a significance level (α) of 0.5, can be followed by one or more backward elimination steps with a significance level (α) of 0.1. The stepwise selection process terminates if no further variable can be added to the model or if the variable just entered into the model is the only variable removed in the subsequent backward elimination (Min, 2005). SMLR starts with

no variables in the model and the basic method of obtaining optimal predictors starts with each *x* variable in the data set; then determines the regression model relating to the y variable and calculates the corresponding regression coefficient which is the residual sum of squares (RSS) in order to assess the model's correlation of the predictor. The most highly correlated variable is then selected as the first variable in the regression model; denoted as x_{s1}. Then regression models with both the pre-selected variable, x_{s1}, and each of the remaining *x* variables are determined using MLR and the corresponding RSS value calculated for each model. The *x* variable that produces the highest RSS when used in combination with x_{s1} then becomes the second selected variable and is denoted, x_{s2}. The process is then repeated until the stepwise selection reaches the desired number of variables selected by the stepwise regression routine equal to the desired number of variables as specified by the operator (Yee and Gimel'farb, 1999). In SMLR, over fitting could be a problem because too many wavelengths might be selected by the stepwise procedure (Min, 2005).

1.7.4.3 Assessment objectives

The main objective of the vine-kill wait period assessments were to determine the effects of time elapsed between vine-kill and harvest on resistance to mechanical damage incurred during the harvesting, grading and packing of Florida new potatoes. This was accomplished by evaluating the damage caused by controlled impacts on tubers dropped from several heights that commonly occur during the harvesting and processing of potatoes. In addition to the main objective, several sub-objectives were:

- Determine the physical properties of potato tubers at various times after vine-killing had been performed on the plants;

- Determine the change in skinning resistance that occurs as potato tubers were allowed to undergo skin set in the soil;
- Determine the effect of short-term storage on the damage resistance of potato tubers at various times after vine-kill.

The two main objectives of the spectral measurement assessments were to determine the important wavelengths in the electromagnetic spectrum to assess if physical damage had occurred internally in the two varieties ‘Fabula’ and ‘Red La Soda’ and to determine the important wavelengths in the electromagnetic spectrum that can be used to detect if internal bruising, greening, scarring or other possible external defects were present. The sub-objectives were to:

- Determine the reflectance changes of ‘Fabula’ and ‘Red La Soda’ caused by moisture content change to assist in the detection of damage.
- Develop a calibration model for damage prediction.

Table 1-1. Mechanical Damage of Potatoes.

Damage Type	Description	Causes
Skinning (Feathering)	The skin layer (periderm) of the potato is partially or completely removed, exposing the underlying tuber flesh.	Immature tubers, high nitrogen availability at harvest, and excessively wet soils.
Shatter bruise	A visible crack forms in the tuber surface which can extend deep into the tuber flesh and causes discoloration around the crack.	Ruptures caused by an impact that results in tissue separation and drying out. Cool harvesting temperatures and exposure to low humidity favor shatter.
Blackspot bruise	Caused by significant impact to the tuber which results in the cell membrane of tissue within a tuber rupturing and causes the formation of a black pigment.	Impacts caused by large tuber size or drops, poor tuber hydration, potassium deficiency, significant curvature and old or very mature tubers.
Pressure bruise	Flattened areas or indentations on the tuber surface. Internally a gray to black discoloration in the flesh occurs.	The result of tissue damage due to a continuous weight being exerted onto the surface. Favored by dehydration of tubers, storage humidity below 90% and excessive pile height.
Cut	The separation of a portion of the potato tuber flesh due to an external force.	The result of tubers coming in contact with the edges of mechanical harvesting devices such as digging blades and the sides of conveyors or sorting tables.

*Compiled from Compendium of Potato Diseases. 2001. The American Phytopathogical Society. St. Paul, Minnesota.

Table 1-2. Classification for degrees of skinning by lot.

Skin rating	Classification
Practically no skinning	Not more than 5 percent of the potatoes in the lot have more than one-tenth of the skin missing or “feathered”
Slightly skinned	Not more than 10 percent of the potatoes in the lot have more than one-fourth of the skin missing or “feathered”
Moderately skinned	Not more than 10 percent of the potatoes in the lot have more than one-half of the skin missing or “feathered”
Badly skinned	More than 10 percent of the potatoes in the lot have more than one-half of the skin missing or “feathered”

* Compiled from USDA Standards for Grades of Potatoes. 2011. USDA AMS, Washington, D.C.

Table 1-3. Physiological defects of potatoes.

Disorder	Description	Causes
Greening	Light enhanced chlorophyll production that results in a green skin. This greening is harmless, but compounds called glycoalkaloids which are harmful to humans also increase in tissue.	Sunlight, indirect daylight or artificial lights enhances chlorophyll production. Tubers developing near the soil surface may be directly exposed to sunlight or through cracks in the soil surface caused by tuber growth.
Sunscald	Tuber surface takes on a blistered, metallic appearance. Underlying tissues may become watery and turn brown. Making tubers predisposed to rot in storage.	Caused by frequent or prolonged exposure of tubers to intense sunlight and high temperature. Threshold tuber flesh temperature for sunscald is 43°C (109°F) and can occur in tubers as deep at 2.5 cm.
Growth Cracking	Shallow to moderately deep fissures in the surface tissue of tubers, usually following the long axis of the tuber.	Caused by internal pressure that exceeds the tensile strength of surface tissues during tuber enlargement. Often caused by an uneven availability of soil moisture and rapid water intake.
Early Blight	Lesions are dark, circular to irregular in shape and sunken in surrounded by a raised purplish-gray border with dry, leathery flesh that is usually brown.	Caused by spores of the fungus *Alternaria solani*, but does infect tubers before harvest. Infection occurs when contaminated soil comes into contact with wounds made during harvest.
Late Blight	Infection is initially somewhat superficial, but lesions can eventually extend several centimeters into the tuber. Lesions are reddish brown, dry and granular.	Caused by the pathogen *Phytophthora infestans*. Tuber infection occurs whenever the potato comes in contact with the pathogen in the soil, often being transported by rain or irrigation.
Dry Rot	Shallow lesions are visible as small brown areas after around 1 month of storage with infection slowly enlarging in all directions. Periderm over the lesion sinks and wrinkles.	Tuber infection occurs at wound sites by the pathogens of *Fusarium* spp. present in infested soil and contaminated equipment.
Brown rot	Vascular tissue of infected tubers has a distinct grayish brown and the discoloration may extend into the pith or cortex. Sticky exudate may form at eyes or stolon.	Caused by the pathogen *Ralstonia solanacearum* infecting the potato plant and spreading into the tubers through the stolon.
Insect damage	Insects bore into tubers superficially, produce tunnels or scratch the skin facilitating penetration of pathogens in the soil.	Caused by insects in the soil eating portions of the tuber

*Compiled from Compendium of Potato Diseases. 2001. The American Phytopathogical Society. St. Paul, Minnesota.

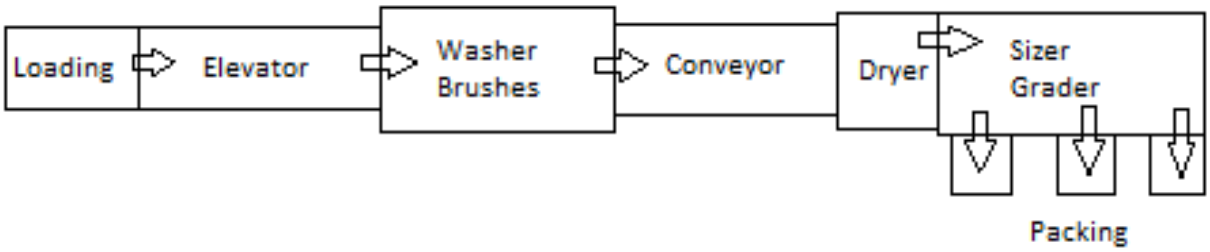

Figure 1-1. Potato route on Hastings Packaging Line

CHAPTER 2
DESTRUCTIVE ASSESSMENT

2.1 Materials and Methods

A total of four tests were performed in order to evaluate the two potato varieties chosen. All sample sets for the two varieties were collected at the same time, and the following four tests were performed; drop impact tests, skinning tests, moisture content tests and compression rupture force tests. Two of the tests were performed in order to determine resistance of the potato periderm to mechanical harvest. These two tests, skinning and drop impact, were simulated in order to estimate the resistance to skinning and bruise damage changes that occur over time after vine-kill for tubers. Moisture content and compression rupture force tests were performed in order to help with the evaluation of changes between harvests.

Tubers used for skinning tests were evaluated for the degree of mechanical damage the day damage testing was applied. Impacted tubers were evaluated for mechanical damage after six days of cold room storage at 20°C and 80% RH in order to allow damage to develop. One skinning test was performed for each variety on the day of harvest, while two drop impact tests were carried out for each variety during every harvest period. The first test was done one day after harvest to determine damage thresholds and the second test was done 7 days after harvest to determine the effect of short term storage on impact thresholds. Two moisture content tests and rupture force tests were performed on each variety corresponding with the drop impact testing times. The properties to be determined over the course of this study were changes in moisture content, skin toughness and resistance to the forms of mechanical damage that often occur during and after harvest; skinning, internal shatter, external shatter, and blackspot bruising.

2.1.1 Potato Plant Materials

Sample tubers of the two new potato varieties, ‘Fabula’ and ‘Red La Soda’ (Figure 2-1), were hand-harvested out of the fields of the University of Florida Research and Demonstration Site in Hastings, Florida and were transported to the Postharvest Horticulture Laboratory of the University of Florida in field lugs. The variety ‘Fabula’ has a very high yield and very large size tuber with pale yellow flesh, and oval barrel-shape. It also has an extremely smooth, light yellow-colored skin with shallow eyes. It was described to have good internal bruising resistance, as well as fairly good to very good resistance to many viruses that effect tubers. Samples were determined to have a mass between 90 and 470 grams during the study. The other variety ‘Red La Soda’ has a white to cream colored tuber flesh, a round to oblong shape and smooth deep red colored skin; eyes are of medium to deep depth and well distributed. It was described to have good skinning resistance, good yield potential and a relatively low specific gravity compared to other red-skinned varieties and a general disease resistance requiring standard disease control programs be followed. Samples were determined to have a mass between 80 and 325 grams during the study.

Initial field samples for 7 days before vine-kill were collected May, 18 2010. Samples for the day before vine-kill were collected on May, 24 2010. The 7, 14 and 21 days after vine-kill samples were collected June, 1st, 8th, and 15th of 2010, respectively. All samples were collected during late morning to noon hours. Normally, potatoes would be harvested mechanically and transported to a packinghouse. But in order to reduce the number of immeasurable impacts and scuffing that can take place during this process, it was decided that physically harvesting tuber samples by hand and sorting for defects in the field would be used for this research (Figure 2-2).

2.1.2 Potato Skinning Tests

Samples for different harvesting periods around vine-kill were tested for mechanical skinning damage using the cleaning section of the packing line present at the UF Hastings farm, (Figure 2-3), this portion of the packaging line included a rubber conveyor to lift potato tubers up from the receiving hopper onto the wash area, which had rotating rollers to move tubers along under the drenching tubes and abrasively clean the tubers. A sample group of (n=20) potato tubers from each variety were run along the cleaning section in order to determine day of harvest skinning that would occur for each harvest period. The samples designated for the packing line skinning test were dumped onto the packing line conveyor, where they were elevated and dropped onto the washer/brush bed. Brush rolls in the wash area conveyed the tubers toward the conveyor which led to the sorting table. The samples were collected at this point for each harvest's experimental run to maintain consistency.

An initial assessment of skinning mechanical damage was done using a nondestructive method immediately after returning from the fields in Hastings, Florida. Due to the difficulty of accurately measuring percent skinning of a tuber, a subjective scale rating was used to assess the skinning damage called Jenkins-Wehner method (Table 2-1). The percent of tubers damaged was compared between harvest periods in order to compare the changes in mechanical damage done as tubers were allowed to mature.

2.1.3 Impact Drop Tests

A test was performed in order to simulate the mechanical damage caused by all the tumbling and dropping during harvesting and handling operations. Individual tubers were held in a sling in order to control the point of impact and prevent rotation (Figure 2-4) the bud end was

chosen due to its smaller curved area of impact. Tubers of each variety (n=10 for each drop height) were dropped from various heights (30 cm, 60 cm, and 90 cm and 120 cm) onto a hard surface in order to perform comparable damage to tubers from each harvest period, and single drop tests were performed in order to evaluate the damage caused by one time impacts, while double impact tests were performed in order to determine if extra damage would be accumulated from repeated impacts on the same location. White chalk dust was spread over the impact area in order to accurately indicate the point of impact for later damage assessment. The procedure was repeated for each variety using various drop heights and tubers of different mass. Drop tests were performed on separate sample groups the day after harvest and 7 days after harvest. The drop heights performed were: 30 cm, 30 cm double drop, 60 cm, 60 cm double drop, 90 cm and 120 cm for the last two harvest periods.

The internal and external mechanical damage assessment was done after tubers were stored in a 20°C (68°F) and 80% RH cold room for six days in order to allow mechanical damage to develop. On the seventh day, the potato tubers were assessed for external and internal mechanical damages in order to identify changing trends caused by vine-kill harvesting times. External mechanical damage assessment was done visually inspecting for skinning and external shatter around the point of impact and measuring the size of the skinned area or length of shatter if present. Internal mechanical damage assessment was done using a destructive method. Potato tubers were sliced along the bud end at the point of impact (Figure 2-5). Once sliced, tubers were visually inspected for development of blackspot bruising and internal shatter (which would lead to external shatter if permitted to continue developing). Internal shatter was assessed by measuring the depth and length of the damage and these diameters were used to calculate the cross sectional area of the internal shatter. Blackspot bruising was assessed by measuring the

length, width and height of damage, as well as, how deep below the surface damage developed. This assessment generally required additional cutting of tuber to allow for more accurate measurement. These three dimensions were used to calculate the volume of blackspot damage to the tuber. The presence of damage, as well as, the volume or cross sectional area of this damage was plotted using bar graphs in order to compare the severity of damage at each point of harvest.

2.1.4 Moisture Content Tests

During each harvest, samples were collected in order to perform moisture content tests on the tuber skin and flesh. This was done in order to compare results between harvests to identify if moisture content level differences and similarities influenced the results of mechanical damage testing between harvests. The moisture content levels of potato tubers were shown in many studies to affect the occurrence of shatter and blackspot bruising. Aluminum sample trays were weighed before the skin of several tubers was peeled off to accumulate a significant weight in each sample tray for dehydrating. Next chunks of tuber flesh were sliced up and weighed and recorded in individual sample trays also. Once the skin and flesh samples for both varieties were collected they were placed in a hot air drying oven kept at 60°C for 2 weeks to allow for complete removal of moisture. Percent moisture content was calculated using wet basis by dividing the total mass of water found from oven drying by the total initial wet mass of material and multiplying the result by 100 to get percent. Samples were collected to coincide with each drop test performed, so moisture content tests were performed the day after harvest and 7 days after harvest as well.

2.1.5 Compression Rupture Force Tests

The compression strength of the two tuber varieties was tested at each point of harvest except for the 7 days before vine-kill group. Cylindrical cores were taken from potato tubers using a metal punch to create 2.22 cm (0.875 in.) diameter, and 2.54 cm (1 in.) tall samples. Using an Instron Universal Testing Instrument (model 4411, Instron, Norwood, MA), a constantly increasing force was applied to samples up to 500 N until samples critically failed under the load ruptured diagonally (Figure 2-6). Compression strength was calculated by dividing the load at critical failure by the cross-sectional area resisting the load and reported in kilopascal (kPa). Just like the previous two tests samples were run 1 day after harvest and 7 days after.

2.2 Results and Discussion

2.2.1 Potato Skinning Tests

Incidences: For the skinning tests performed on ‘Fabula’ tubers harvested 7 days before vine-kill, a significant extent of skinning showed up on tuber samples used (Figure 2-7). However, after vine-kill was performed there was a sharp decline in the number of tuber samples which displayed over 10% skinning or feathering area from 60% to 0% with just 7 days of skin set (Figure 2-8). As the weeks after vine-kill increased there was an insignificant change in the percent of potato tubers which displayed skinning damage between weeks which indicates that 7 days of waiting allowed skins to set enough for harvesting operations.

In contrast to the results for ‘Fabula,’ the skinning tests performed on ‘Red La Soda’ tubers before vine-kill resulted in many tuber samples with little to no skinning, which was to be expected from the skinning resistant variety ‘Red La Soda’ (Figure 2-9). After vine-kill was

performed there was little to no change in the number of tuber samples which displayed significant skinning or feathering for any period of wait for skin set (Figure 2-9). As the days after vine-kill increased there was an insignificant change in skinning incidents on tubers which suggested that 7 days of waiting allowed skins to set enough for harvesting operations.

Severity: The severity of skinning that resulted from testing with 'Fabula' showed significant change between pre vine-kill and post vine-kill tubers (Figure 2-8). 'Fabula' tubers harvested after vine-kill showed little or no skinning damage, while the majority of those harvested before vine-kill showed skinning. The USDA standards dictate that because of the quantity of tubers skinned and the severity of skinning for 7 days before vine- kill the harvest would have to be classified as "Badly Skinned" as a result of 10 percent of the samples missing half of their skin. The 'Fabula' tubers harvested the day before vine-kill faired a little better due to less severe skinning that resulted in the classification of "Moderately Skinned" due to skinning resulting in more than 10 percent of the tubers being skinned more than 25% of their total surface area. The 'Fabula' tubers harvested 7 days after vine-kill ended up with the best results due to most skinned tubers only suffering 3-6% skinning which allowed them to pass with the least skinning damage and the classification "Practically No Skinning". The last two harvest periods, 14 and 21 days after vine-kill, resulted in somewhat significant skinning results on a few tubers which qualified them for the USDA classification "Slightly Skinned".

The severity of skinning resulting from the experiment on 'Red La Soda' showed insignificant changes between pre vine-kill and post vine-kill tubers (Figure 2-10). The skinning damage that occurred on the two harvests before vine-kill were insignificant by the USDA standards and would be classified as "Practically No Skinning" without any skin setting being initiated on the potato tubers. The potato tubers harvested 7 and 14 days after vine-kill ended up

with the worst results due to over 5% of ‘Red La Soda’ tubers suffering at least 10% skinning which classified them as “Slightly Skinned”. The last period of harvest, 21 days after vine-kill, resulted in such insignificant skinning results on a few tubers which qualified them for the USDA label “Practically No Skinning” with the least skinning resulting during skinning simulation.

2.2.2 Impact Drop Tests

The following types of mechanical damage were observed in the impact drop tests for both ‘Fabula’ and ‘Red La Soda’; external shatter, blackspot bruising, and skinning. The results of impact testing for both varieties displayed effects similar to those reported by Thornton and Bohl (1998) in which greater drop heights resulted in a larger force that caused bruising to occur more often.

2.2.2.1 ‘Fabula’

Incidences: Two types of external damages (skinning and external shatter) were observed in samples of ‘Fabula’ receiving impact damage, while only one type of internal damage (blackspot bruising) was observed. The most common form of mechanical damage observed on ‘Fabula’ samples was skinning (Figure 2-11 and 12), followed by blackspot bruising (Figure 2-13 and 14), and only one incident of shatter (Figure 2-15 and 16); similarly, Chiputula et al. (2009) reported the major mechanical damage found during sample collection from harvesting and packaging of the varieties ‘Fabula’ and ‘Yukon Gold’ to be skinning, which would be expected with two varieties that have more resistance to bruising than skinning. However, the results of impact testing performed by Chiputula et al. (2009) resulted in many incidences of external shatter, internal shatter and black spot bruising, but oddly found no cases

of skinning. Skinning incidents for ‘Fabula’ tubers harvested before vine-kill appeared to be unaffected by drop height, with most tubers skinning regardless of height. The three harvests after vine-kill had a large drop in skinning frequency of 20-40% for all drop heights and often required a significant drop of 90 cm or consecutive drops at 30 cm and 60 cm in order to develop skinning damage, and only in decreasing significance as time after vine-kill increased (Figure 2-11). Storage of ‘Fabula’ tubers only helped reduce the occurrence of skinning damage for the harvest period 7 days after vine-kill.

Blackspot bruising was not observed day after picking in two harvests, 7 days before vine-kill and 14 days after vine-kill. Storage of 7 days for those harvested 7 days after vine-kill allowed tubers to completely resist bruising, (Figure 2-13). Bruising occurrence dropped 20-30% 7 days after vine-kill from the day before vine-kill and 30-40% for the following last two harvest periods. Incidences of bruising for the periods that displayed bruising tended to decrease over time and ended up only resulting from impacts with more force exerted on the tuber. The only occurrence of external shatter was during the last harvest period from one of the tubers used in a 60 cm double drop test.

These results vary greatly from the results of impact testing done by Chiputula et al. (2009) in which a drop above 90 cm was required for any damage to appear. These results involved a large occurrence of internal bruising and shatter development, which was likely encouraged by the much higher moisture content levels around 92-95% for the ‘Fabula’ samples collected and tested.

Severity: The severity of skinning damage from drop impacts was much more substantial during the two harvests before vine-kill (Figure 2-12). Skinning damage area dropped

significantly in comparison to the day before vine-kill harvest with only 7 days of vine-kill skin set with drops of 90 cm being required to skin a remarkable area of the impact zone. Skinning damage for the remaining harvests and extra 7 days storage were even further reduced for the few tubers observed with damage. Blackspot bruising in 'Fabula' tended to occur in very minimal dimensions except for one incident during the 7 days after vine-kill harvest when a bruise formed with a volume over 1 cubic cm which was an extreme outlier when compared to all over bruising volumes (Figure 2-14). The external shatter which occurred on a single 'Fabula' tuber during the 21 days after vine-kill harvest was severe enough to cause 2.54 cm of damage to the exterior of the tuber, but was only 1/3 the length of the tuber making it less serious damage according to the USDA.

Mass: The mass of 'Fabula' tubers dropped was measured in order to determine how much of a role tuber mass played in damage development. Skinning occurrence versus tuber mass (Figure 2-17), skinning area versus tuber mass (Figure 2-18), bruising occurrence versus tuber mass (Figure 2-19), bruising volume versus tuber mass (Figure 2-20), and shatter occurrence versus tuber mass (Figure 2-21). When comparing the mechanical damage that occurred for 'Fabula' versus the mass of tubers dropped, it becomes obvious that drop height plays a slightly larger role in damage development than mass. Skinning and bruising incidents tend to occur at a higher rate when the drop height was 60 cm or more regardless of tuber mass as can be seen in (Figure 2-17 and 19). The skinning area damage was also more significantly dependent upon drop height than tuber mass (Figure 2-18).

2.2.2.2 'Red la soda'

Incidences: Two types of external damages (skinning and external shatter) were observed in samples of 'Red La Soda' receiving impact damage, and two types of internal damage (blackspot bruising and internal shatter) were observed. The most common form of mechanical damage observed on 'Red La Soda' samples was skinning (Figure 2-22 and 23), followed by blackspot bruising (Figure 2-24 and 25), than external and internal shatter (Figure 2-26 and 27) which damaged tubers to an extent that would lower the USDA grade the most significantly; this was the same result for impact testing by Chiputula et al. (2009) one week after harvest for the varieties 'Fabula' and 'Yukon Gold'. Skinning incidents for the two groups of 'Red La Soda' tubers harvested before vine-kill appeared to be unaffected by severity of drop height, with large quantities of tubers developing skinning regardless of height; over 60% for each category 7 days before vine-kill and over 40% for each category the day before vine-kill developed skinning damage. With just 7 days of storing the tubers harvested the day before vine-kill skinning damage decreased 40-50% for lower drop heights while skinning dropped less for higher drop heights (20-40%). The three harvests after vine-kill showed a significant drop of over 40% less skinning damaged than previous test periods caused from the drop impact force. Storage for these harvests had a less significant influence on skinning occurrence than the day before vine-kill due to already low skinning rates with skinning damage actually increasing slightly for some drop heights (Figure 2-22).

Blackspot bruising was fairly uncommon in 'Red La Soda' and was not observed in two harvests, 7 days before vine-kill and 14 days after vine-kill, as well as after storage of the 14 days after harvest (Figure 2-24). Incidences of bruising for the periods that displayed it tended to decrease over time after vine-kill at lower drop heights and ended up only resulting from impacts

with more force exerted on the tuber of double 60 cm and 90 cm in the last testing period (21 days after vine-kill) and not at all during the 14 days after vine-kill harvest. Shatter tended to develop from drops of greater height and overall impact in 'Red La Soda' tubers, such as 90 cm and 60 cm double drop and only very sparingly (Figure 2-26).

Although the results of impact testing for 'Red La Soda' resulted in more shatter than 'Fabula,' it does not compare to the high shatter occurrence reported by Chiputula et al. (2009) for 'Fabula' and 'Yukon Gold'. Similarly to the results for 'Fabula,' this is most likely due to the much high moisture content levels reported for both 'Fabula' (92-95%) and 'Yukon Gold' (91-93%) in the study.

Severity: The severity of skinning damage from drop impacts was much more substantial during the two harvests before vine-kill and increased for higher drops (Figure 2-23). 7 days of storage at day before vine-kill harvesting caused skinning area damage to decrease significantly to around half the previous skinning area. Skinning area damage dropped significantly with only 7 days of vine-kill skin set with any impact skinning being slight and insignificant. Blackspot bruising in 'Red La Soda' tended to occur in very minimal dimensions at lower impact heights, while higher drop heights resulted in much more significant damage volume up to five times as large as smaller drop heights (Figure 2-25). Time after vine-kill caused bruising volume to drop much more significantly 14 days after vine-kill, with only 7 days slightly dropping average volume an insignificant amount of 10% at the 90 cm drop height. Shatter that occurred on samples of 'Red La Soda' tubers were very significant for the double drop at 60 cm and 90 cm; with often as much as half the length of the sample tubers getting up to 3 cm or more shatter damage (Figure 2-27). Increased harvest time after vine-kill was not able to significantly affect the amount of shatter.

Mass: The mass of ‘Red La Soda’ tubers dropped was measured in order to determine how much of a role tuber mass played in damage development. Skinning occurrence versus tuber mass (Figure 2-28), skinning area versus tuber mass (Figure 2-29), bruising occurrence versus tuber mass (Figure 2-30), bruising volume versus tuber mass (Figure 2-31), and shatter occurrence versus tuber mass (Figure 2-32). When comparing the mechanical damage that occurred for ‘Red La Soda’ versus the mass of tubers dropped, it becomes obvious that drop height plays a slightly larger role in damage development than mass just like with ‘Fabula’. Skinning and shatter incidents tended to occur at a higher rate when the drop height was 60 cm or more regardless of tuber mass (Figure 2-28 and 32), while bruising results appeared to be random with more bruising occurring with tubers of smaller mass at lower drop heights (Figure 2-30). The skinning area and bruising volume damage were also more dependent upon drop height than tuber mass (Figure 2-29 and 31).

2.2.3 Moisture Content Tests

The moisture content levels for both varieties were determined at each point of harvest and after 7 days of storage, the results for ‘Fabula’ (Figure 2-33) and ‘Red La Soda’ (Figure 2-34). The flesh of ‘Fabula’ tubers varied between 81% and 87% moisture content and the skin varied between 82% and 89% over the course of testing, while the flesh of ‘Red La Soda’ tubers varied between 77% and 84% moisture content while the skin varied between 82% and 90%. Similar to the ‘Fabula’ and ‘Yukon Gold’ samples collected by Chiputula et al. (2009) the two tuber varieties used were harvested from the same soil conditions, which would attribute the differences in moisture content to their different physical properties and cause the potato tubers to resist damage differently. The moisture content of tuber skins tended to be slightly higher at

each testing period for ‘Fabula,’ while the moisture content of skin appeared to swing up and down for both varieties.

More incidences of skinning occurred during testing when the skin moisture content of ‘Fabula’ was much higher than the moisture content of the flesh which likely caused the skin to more easily slip off. In contrast, the skin moisture content of ‘Red La Soda’ appeared to only have a slight effect on the occurrence of skinning damage which occurred during skinning testing, but skinning damage caused by drop impacts was still influenced by the difference in moisture content between skin and flesh.

Shatter damaged in ‘Red La Soda’ tended to occur when the moisture content of tuber flesh was above 79% at higher drop heights. On the other hand, incidences of blackspot bruising in tubers appeared to be unaffected by moisture content levels of tuber flesh, which could mean that ‘Red La Soda’ is naturally able to resist blackspot bruising regardless of moisture content. Similarly, the only incident of shatter in ‘Fabula’ occurred when the average moisture content of tuber flesh was near its highest. On the other end of the moisture scale incidences of blackspot bruising in ‘Fabula’ tubers occurred at higher rates during periods in which tuber flesh was below 85% moisture content. These results appear to follow the guidelines for mechanical damage compiled by Stevenson et al. (2001), which states that poor tuber hydration encourages bruising, while better hydration encourages shatter as a result of tubers having a more solid structure.

2.2.4 Compression Rupture Force Tests

The results of compression failure tests for ‘Fabula’ (Figure 2-35), while the results for ‘Red La Soda’ (Figure 2-36). The results of rupture force testing for both varieties oddly follow a

similar trend as moisture content skin results over the weeks of harvest with higher skin moisture content meaning higher required rupture force, except for the very last sample set. The standard deviation for both varieties showed that failure loadings were close enough to have no significant difference, but could possibly show how much load the potato varieties could hold from the bottom of a potato pile.

2.3 Summary

The potato variety ‘Fabula’ was described as a bruising resistant cultivar and the results showed ‘Fabula’ to be more resistant to developing bruising damage than ‘Red La Soda’. While the potato variety ‘Red La Soda’ was reported to be a skinning resistant cultivar, the results of skinning testing confirmed this due to very small occurrence of skinning compared to ‘Fabula’. During testing both varieties ‘Fabula’ and ‘Red La Soda’ displayed development of the following types of mechanical damage to some degree; skinning, blackspot bruising, and external shatter. The results of testing agree with the conclusions of Blahovec (2005) and Chiputula et al. (2009) that mechanical damage outcomes only slightly depended on cultivation regime and a potato varieties damage resistance could impact mechanical damage more than conditions during the growing season.

Three types of mechanical damage were observed during impact testing of ‘Fabula’; skinning, blackspot bruising and external shatter. The main grade decreasing mechanical damage that occurred in the impact drop testing for the cultivar ‘Fabula’ was skinning. The complete absence of skinning from impact simulation could be due to samples being collected after 3-4 weeks of skin set have been allowed. Four types of mechanical damage were observed during impact testing of ‘Red La Soda’; skinning, blackspot bruising, external and internal shatter. The

main grade decreasing mechanical damage that occurred in the impact drop testing for the cultivar ‘Red La Soda’ was external and internal shatter; which can be attributed to high moisture content levels in the flesh of tuber samples.

Incidences and severity of mechanical damage generally increased with drop height for both varieties, with blackspot bruising occurrence being replaced by external shatter at higher drop heights for the variety ‘Red La Soda’. Comparison of data indicated that low moisture content flesh resulted in higher incident rates of blackspot bruising in ‘Fabula’, while high moisture content flesh resulted in higher incident rates of shatter in ‘Red La Soda’ agreeing with the guidelines of Stevenson et al. (2001). The variation of damage between the two varieties could also be associated with the damage resistance and threshold differences referenced by Bajema and Hyde (1998) which had an effect on mechanical damage results during testing. It was observed that impact forces experienced by potato tubers greatly depended on drop height and mass of tubers (Figure 2-37).

Overall, there was more skinning in ‘Fabula’ samples than ‘Red La Soda’ during skinning simulation on the cleaning portion of a packaging line, while drop impact testing resulted in a similar occurrence rate of skinning in both varieties, but ‘Fabula’ had nearly twice the skinned area in affected samples. This could mean that ‘Red La Soda’ is resistant to the skinning associated with rubbing against surfaces, but is susceptible to skinning which can occur when a small amount of surface area is exposed to large external forces from impact which breaks the bond between the skin and flesh. The results of skinning and impact testing before and after vine-kill for ‘Fabula’ agreed with the conclusion of Olson and Simonne (2006), which stated that tubers harvested from living vines were more likely to be severely skinned and/or bruised during harvest. While this result only occurred with ‘Red La Soda’ for impact testing,

this could be attributed to the varieties resistance to skinning. Both varieties experienced minor to extreme drops in mechanical damage occurrence with just 7 days of skin set after vine-kill, depending on how much mechanical damage physically occurred before vine-kill. These results coincide with those found by Hutchinson and Stall (2007), in which proper tuber maturity at harvest improves skin set and bruising resistance in order to produce high quality fresh market potatoes. The significant drop in mechanical damage occurrence with just 7 days of skin set from vine-killing should allow farmers to harvest earlier than the standard 2-3 weeks if weather conditions could cause crop left in the soil longer to be exposed to circumstances that would threaten tuber health.

Table 2-1. Jenkins-wehner damage rating scale

Skinning scale	Minimum skinning	Maximum skinning	Equivalent USDA rating
0	0%	0%	Practically no skinning
1	0.1%	3%	Practically no skinning
2	3.1%	6%	Practically no skinning
3	6.1%	12%	Slightly skinned
4	12.1%	25%	Slightly skinned
5	25.1%	50%	Moderately skinned
6	50.1%	75%	Badly skinned
7	75.1%	87%	Badly skinned
8	87.1%	99.9%	Badly skinned
9	100%	100%	Badly skinned

Figure 2-1. ‘Fabula’ (left) and ‘Red La Soda’ (right).

Figure 2-2. Hand-harvesting potato tubers prior to vine-kill. ‘Red La Soda’ on left, ‘Fabula’ on right.

Figure 2-3. Packing line washer section used for at-harvest skinning test.

Figure 2-4. Drop test stand using sling.

Figure 2-5. A sliced ‘Red La Soda’ with damage (left), and sliced ‘Fabula’ with damage (right).

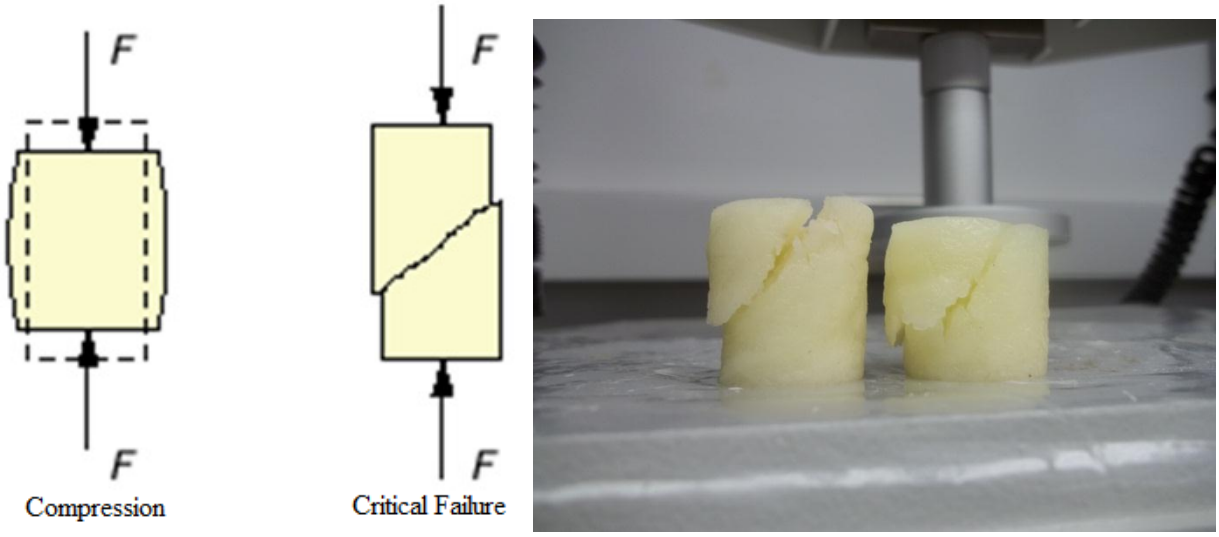

Figure 2-6. Response of tissue to compression force. Compressing and critically failure tuber tissue (left). Photo of critically failed tuber tissue (right).

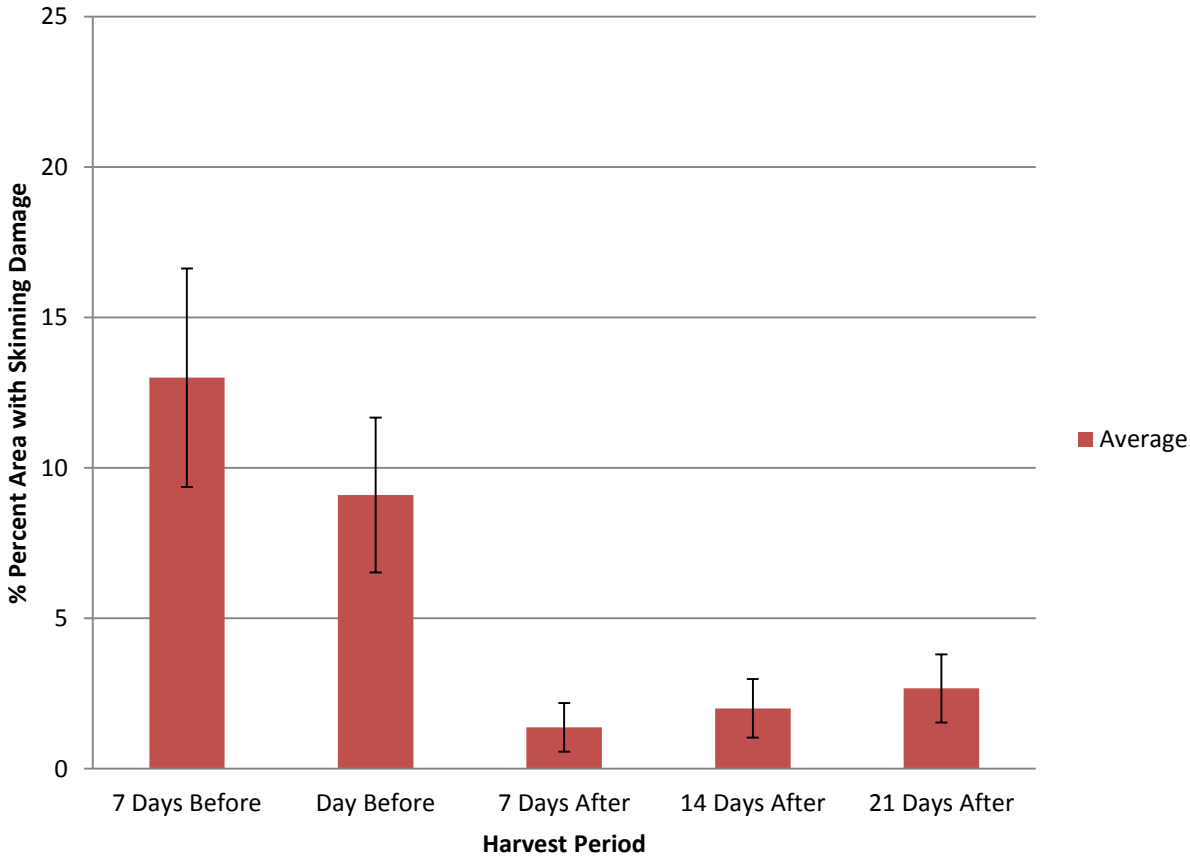

Figure 2-7. 'Fabula' Average skinning damage resulting from packing line handling as affected by harvest time (n=20).

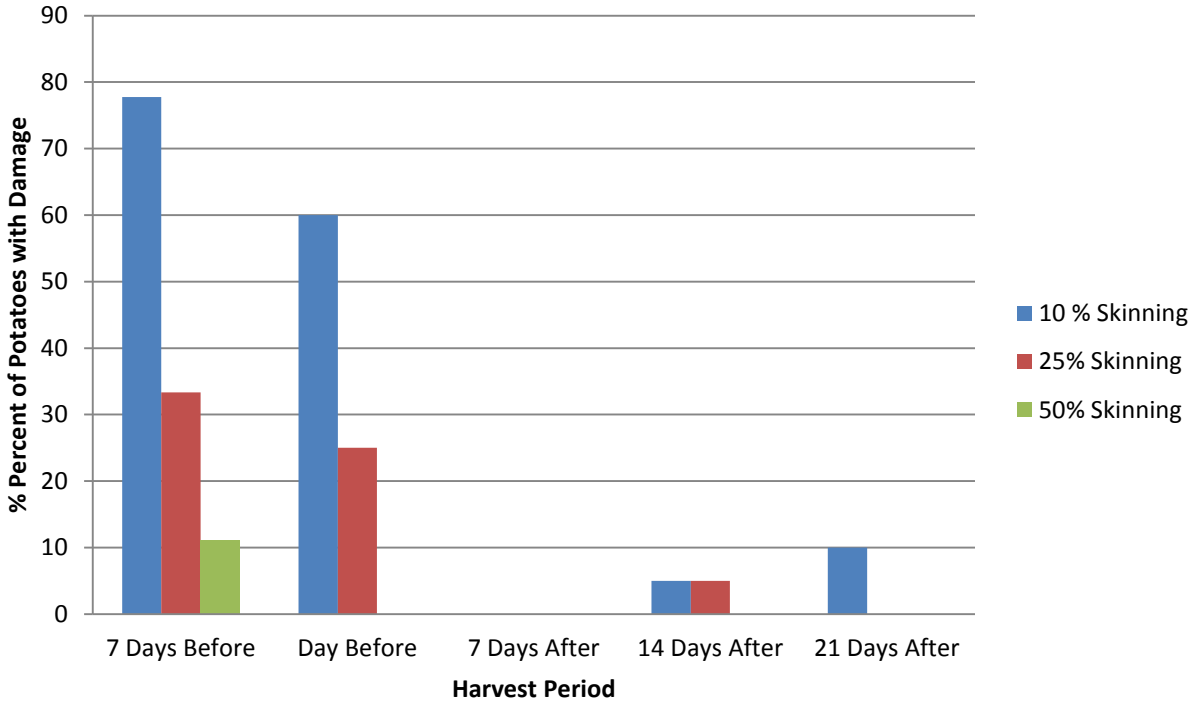

Figure 2-8. 'Fabula' Percent skinning according to USDA grade standards for potato as affected by skinning (n=20).

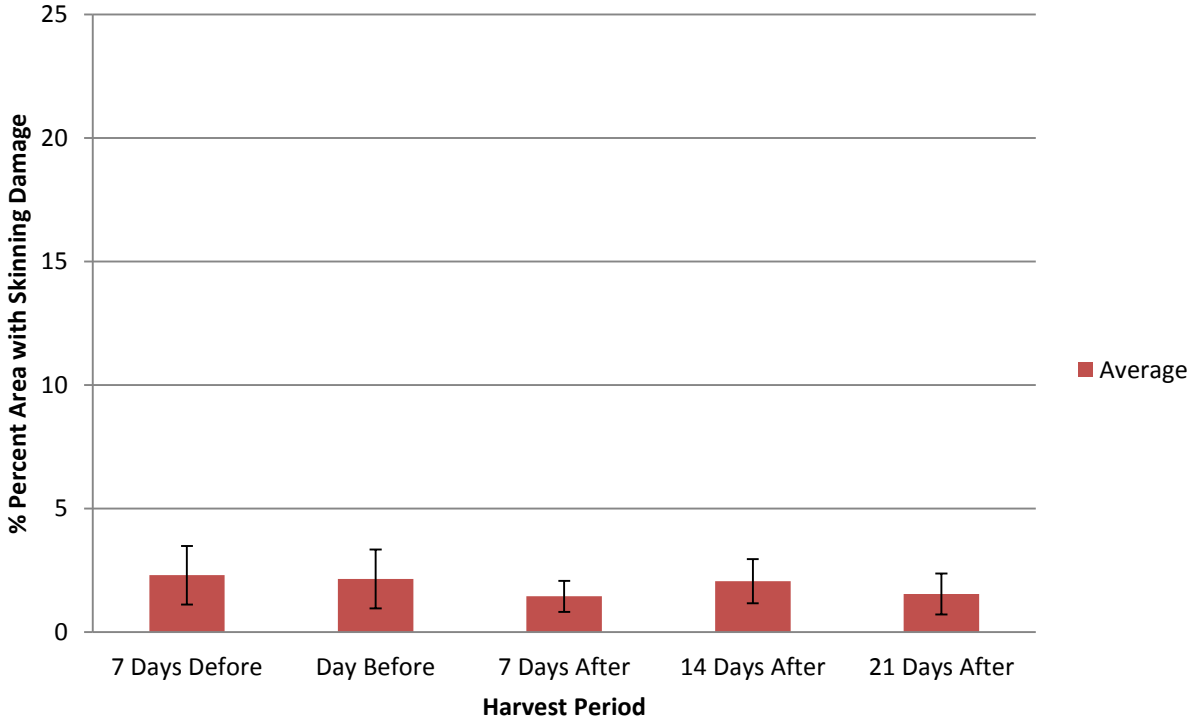

Figure 2-9. 'Red La Soda' Average skinning damage resulting from packing line handling as affected by harvest time (n=20).

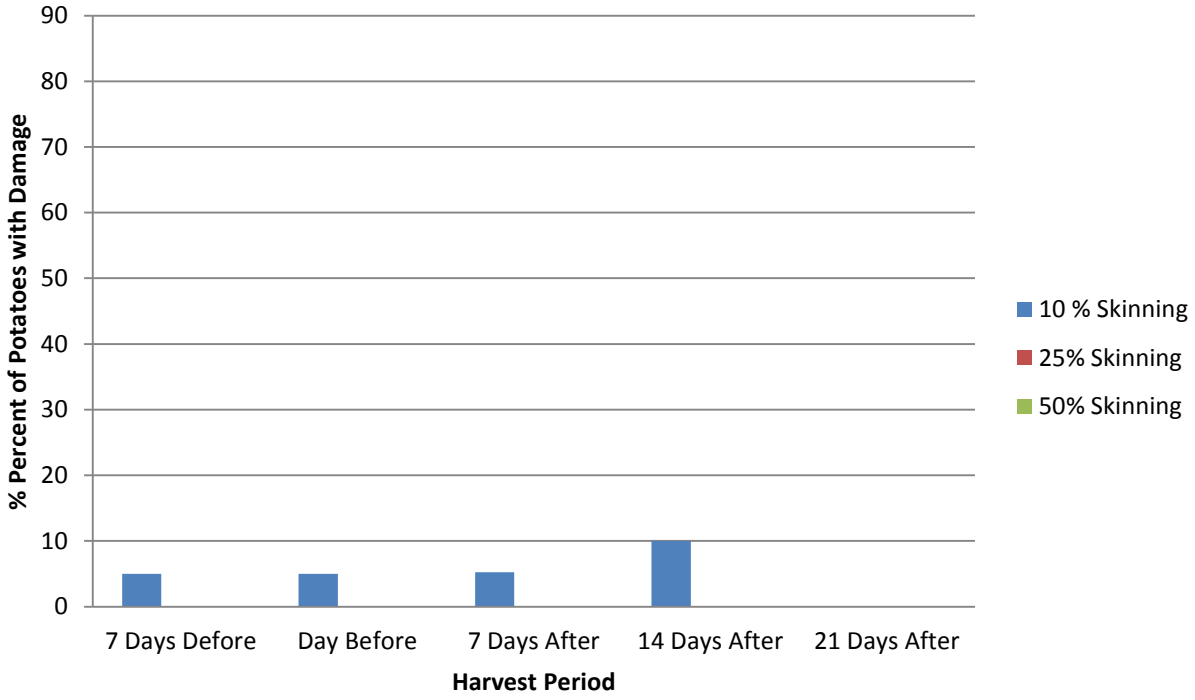

Figure 2-10. 'Red La Soda' Percent skinning according to USDA grade standards for potato as affected by skinning (n=20).

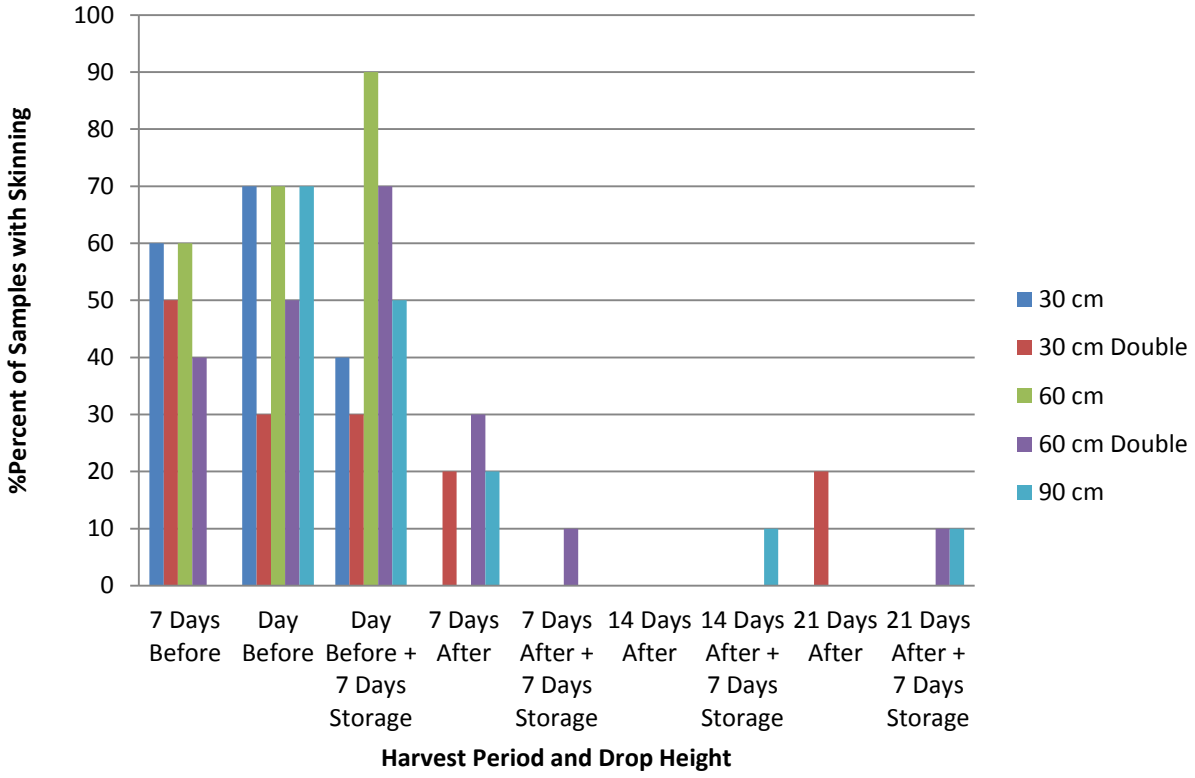

Figure 2-11. 'Fabula' Percent of samples with skinning from impact testing (n=10 per category).

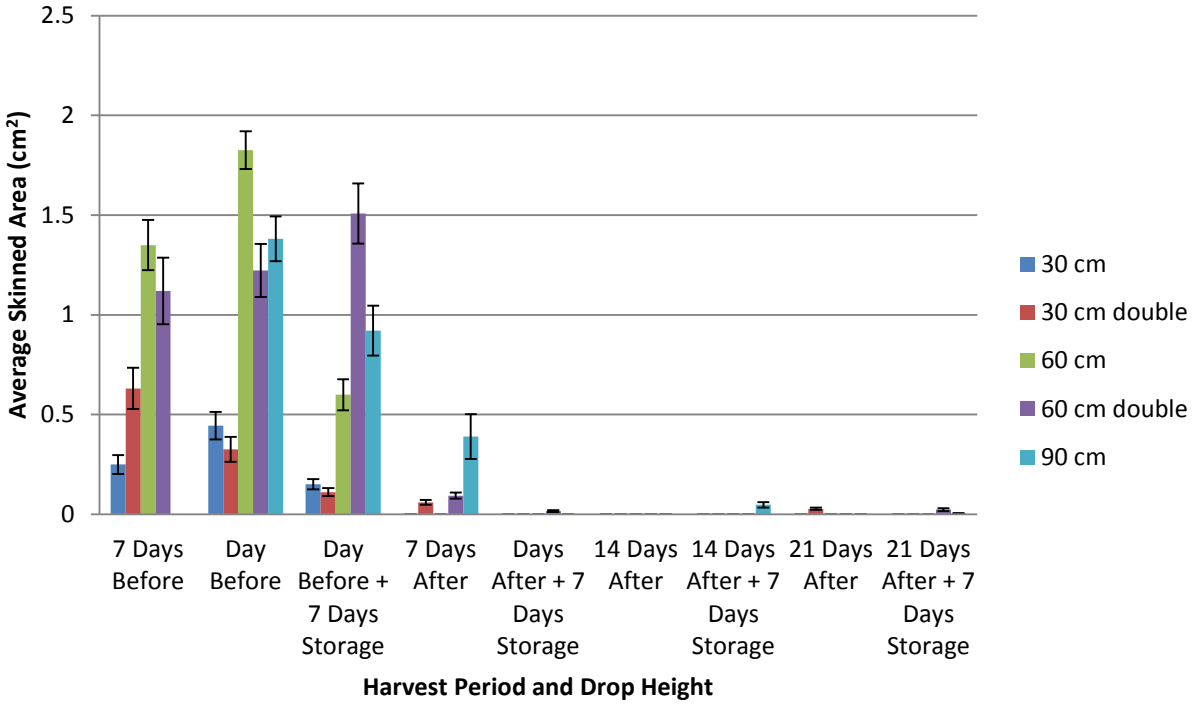

Figure 2-12. 'Fabula' Average skinning area of tubers from impact testing (n=10 per category).

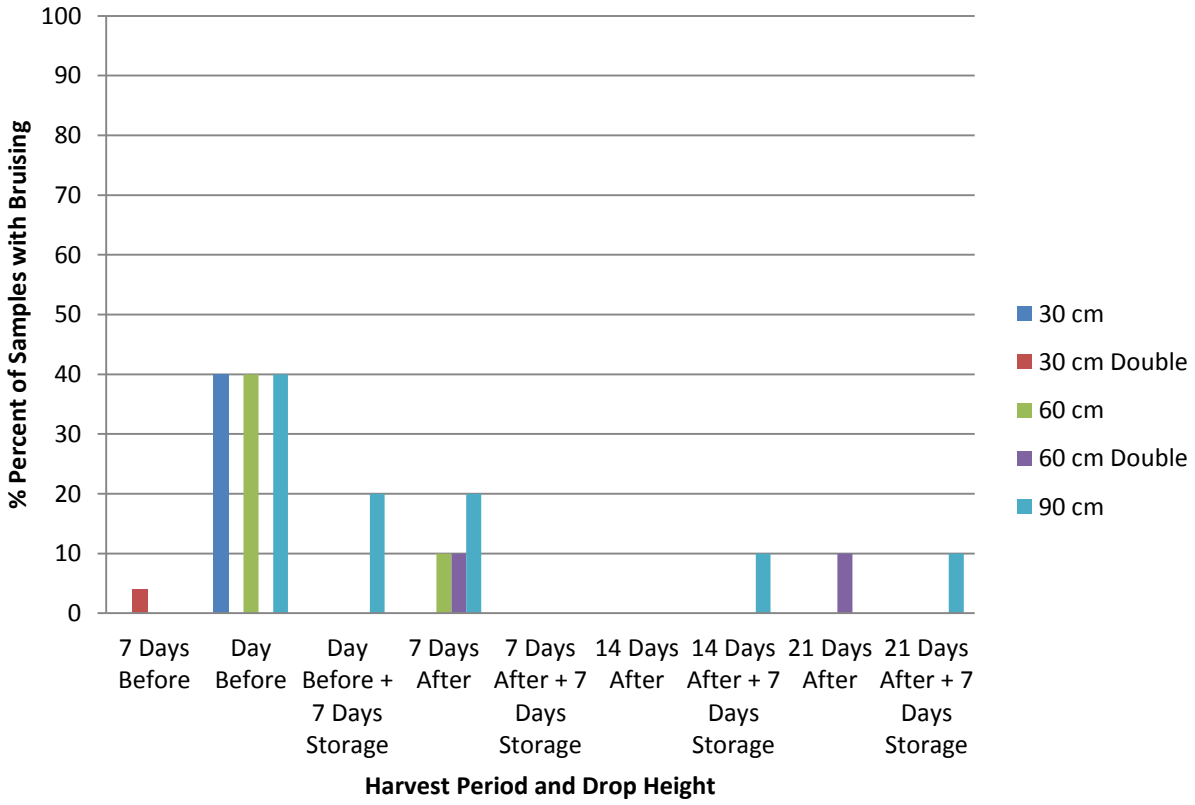

Figure 2-13. 'Fabula' Percent of samples with bruising from impact testing (n=10 per category).

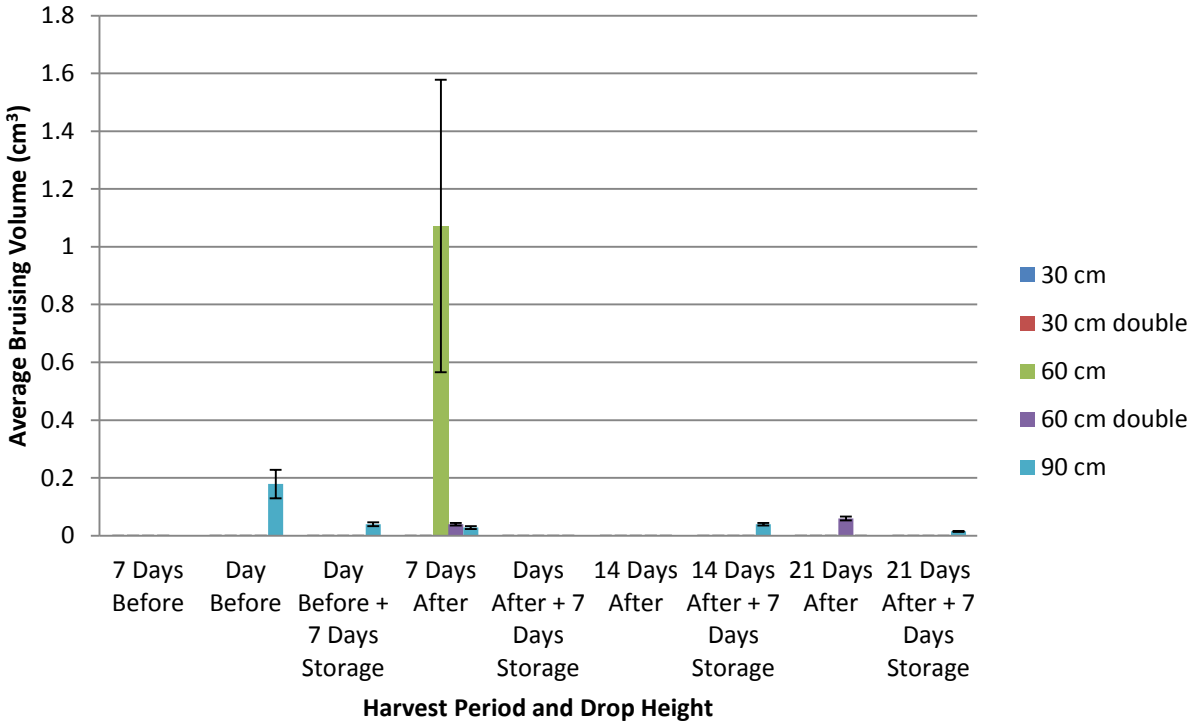

Figure 2-14. 'Fabula' Average bruising volume of tubers from impact testing (n=10 per category).

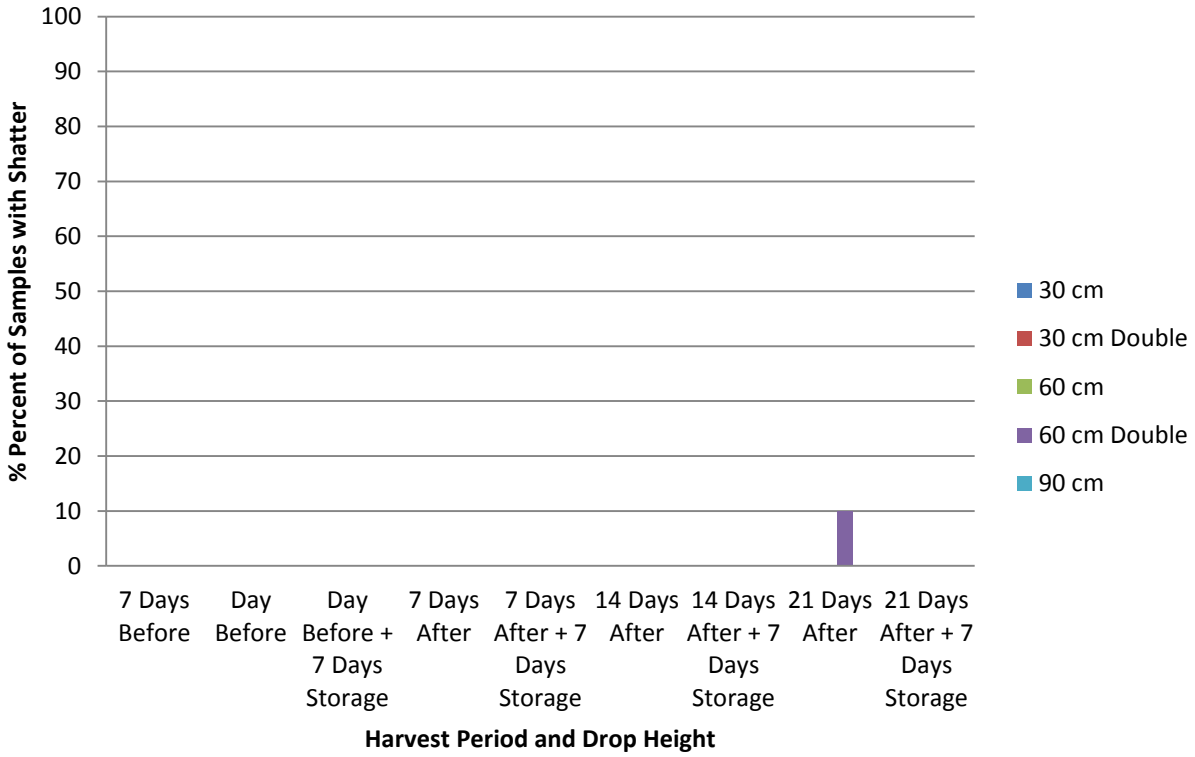

Figure 2-15. 'Fabula' Percent of samples with shatter from impact testing (n=10 per category).

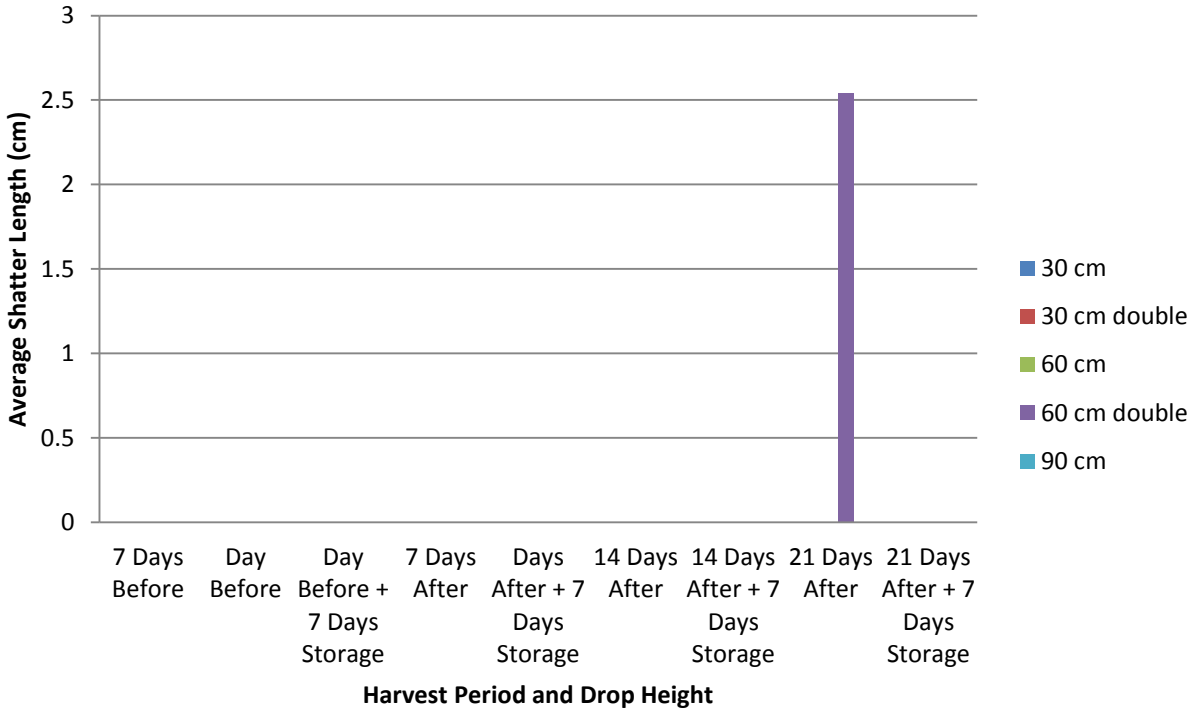

Figure 2-16. 'Fabula' Average shatter length of tubers from impact testing (n=10 per category).

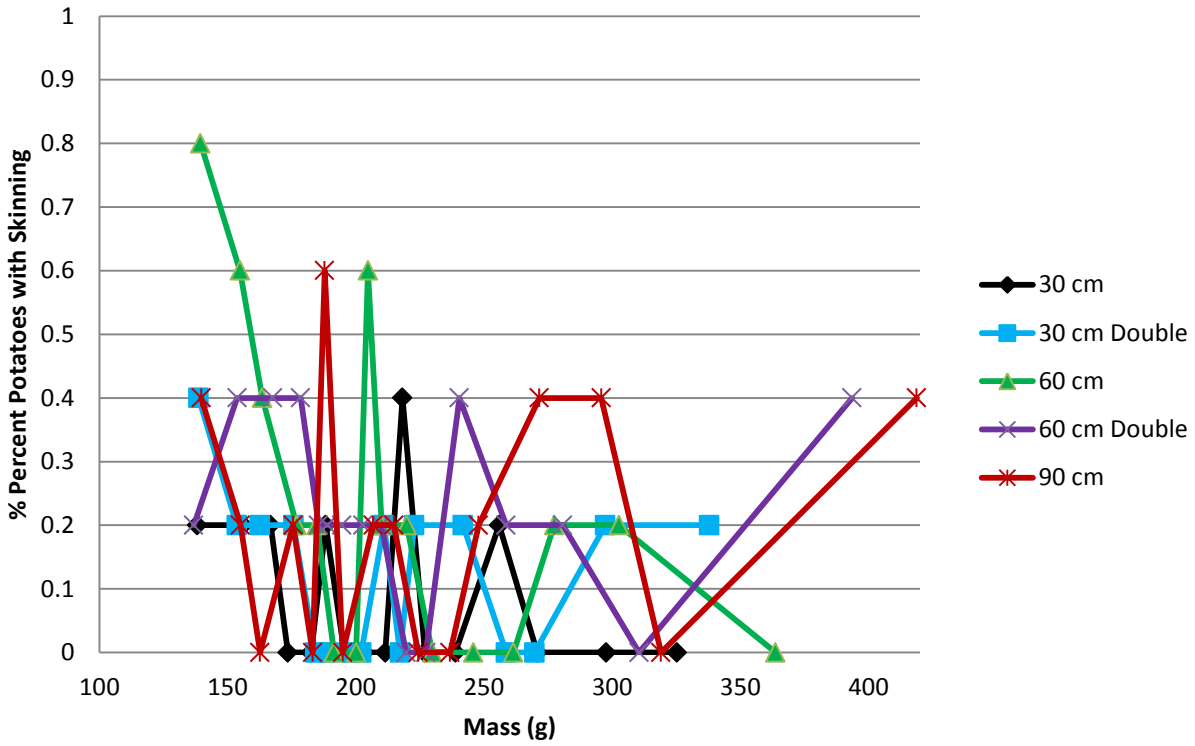

Figure 2-17. 'Fabula' Mass of tubers versus percent tubers with skinning damage from impact testing (n=70 per category).

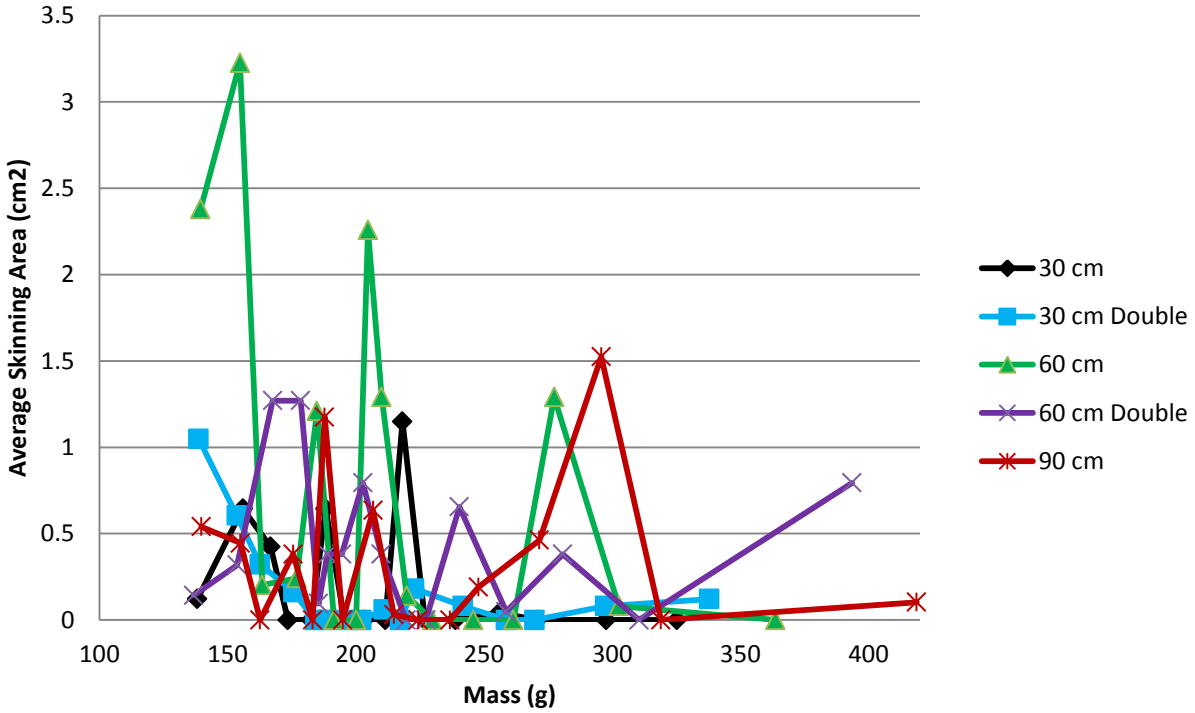

Figure 2-18. 'Fabula' Mass of tubers versus average skinning damage area from impact testing (n=70 per category).

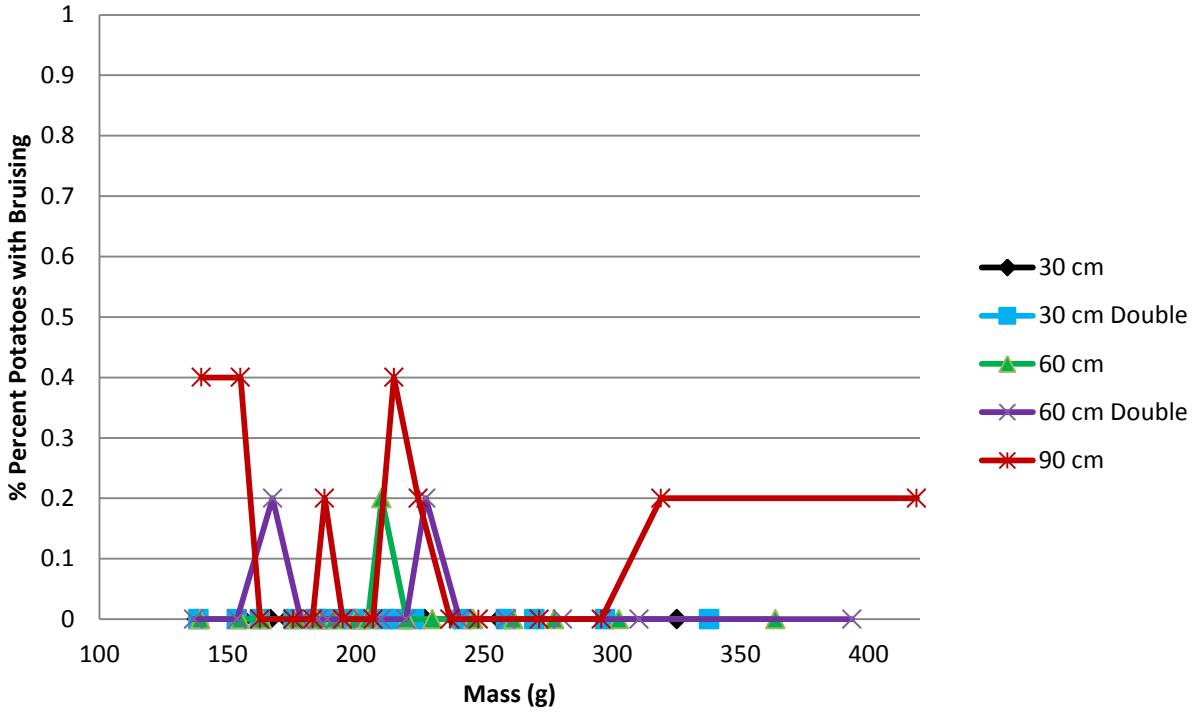

Figure 2-19. 'Fabula' Mass of tubers versus percent tubers with bruising damage from impact testing (n=70 per category).

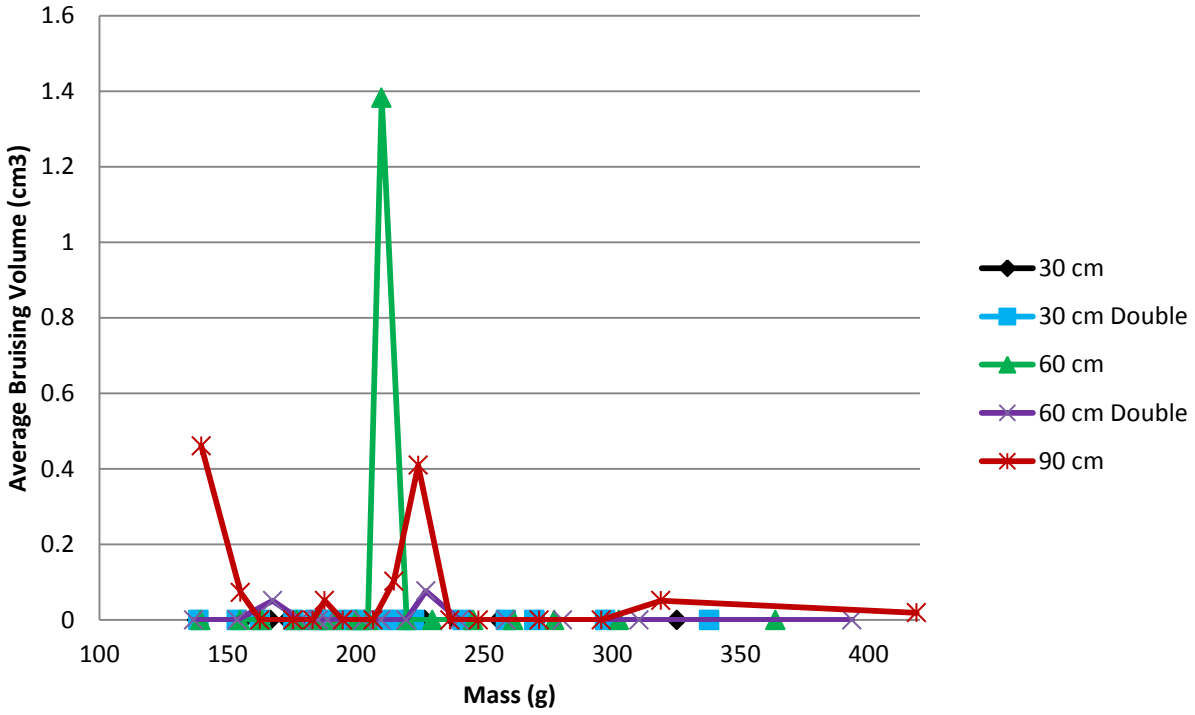

Figure 2-20. 'Fabula' Mass of tubers versus average bruising damage volume from impact testing (n=70 per category).

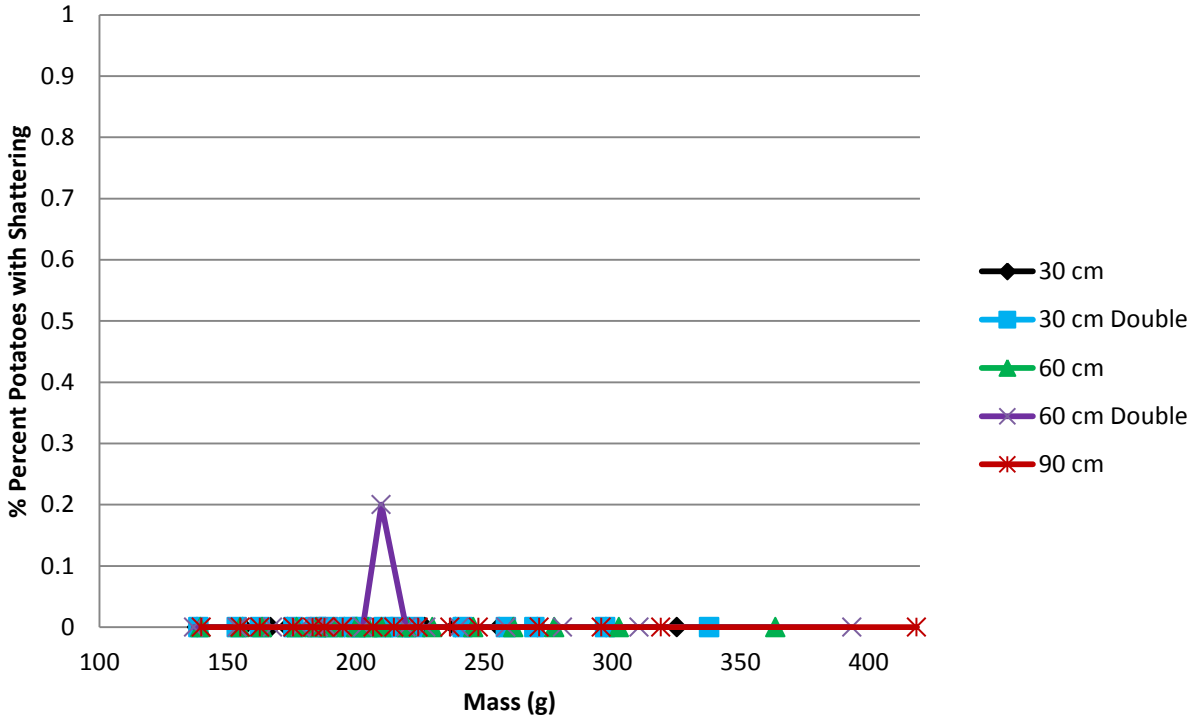

Figure 2-21. 'Fabula' Mass of tubers versus percent tubers with shatter damage from impact testing (n=70 per category).

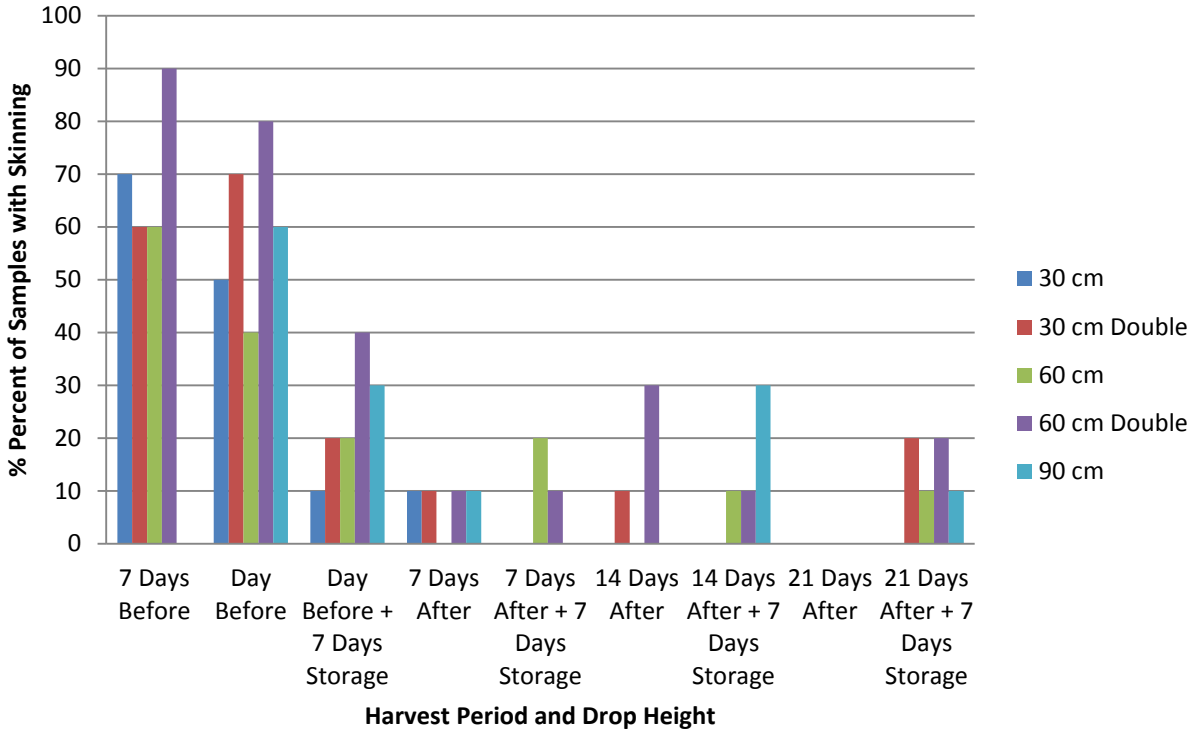

Figure 2-22. 'Red La Soda' Percent of samples with skinning from impact testing (n=10 per category).

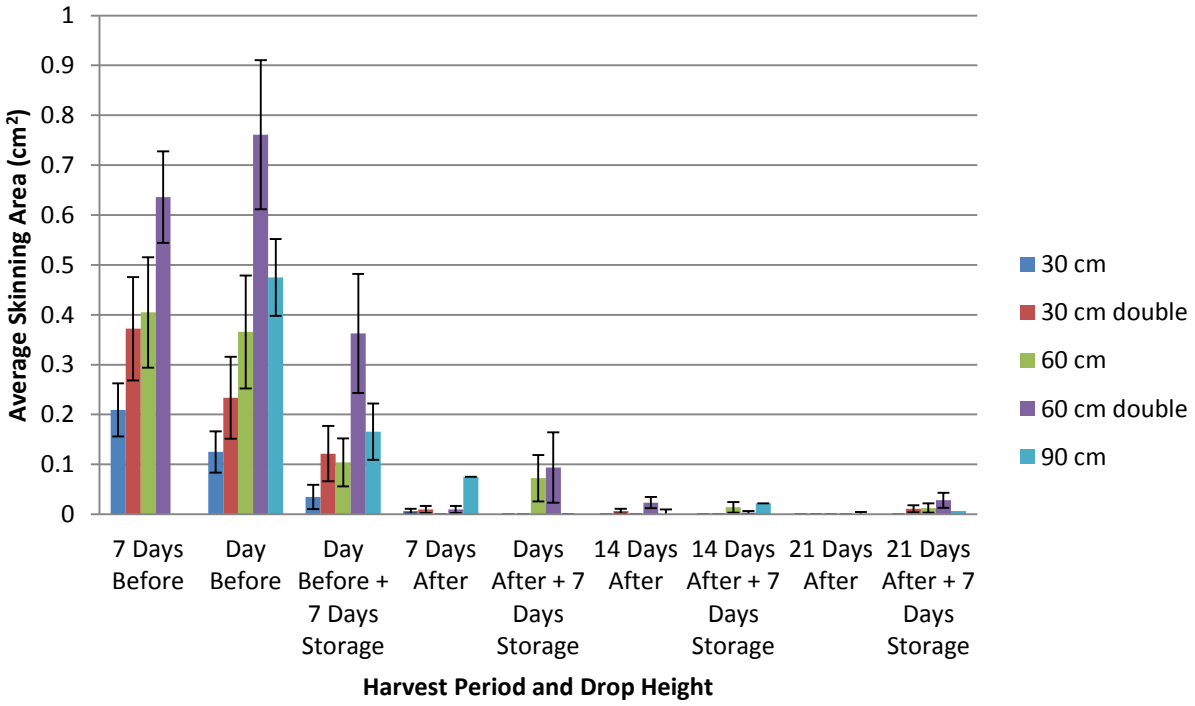

Figure 2-23. 'Red La Soda' Average skinning area of tubers from impact testing (n=10 per category).

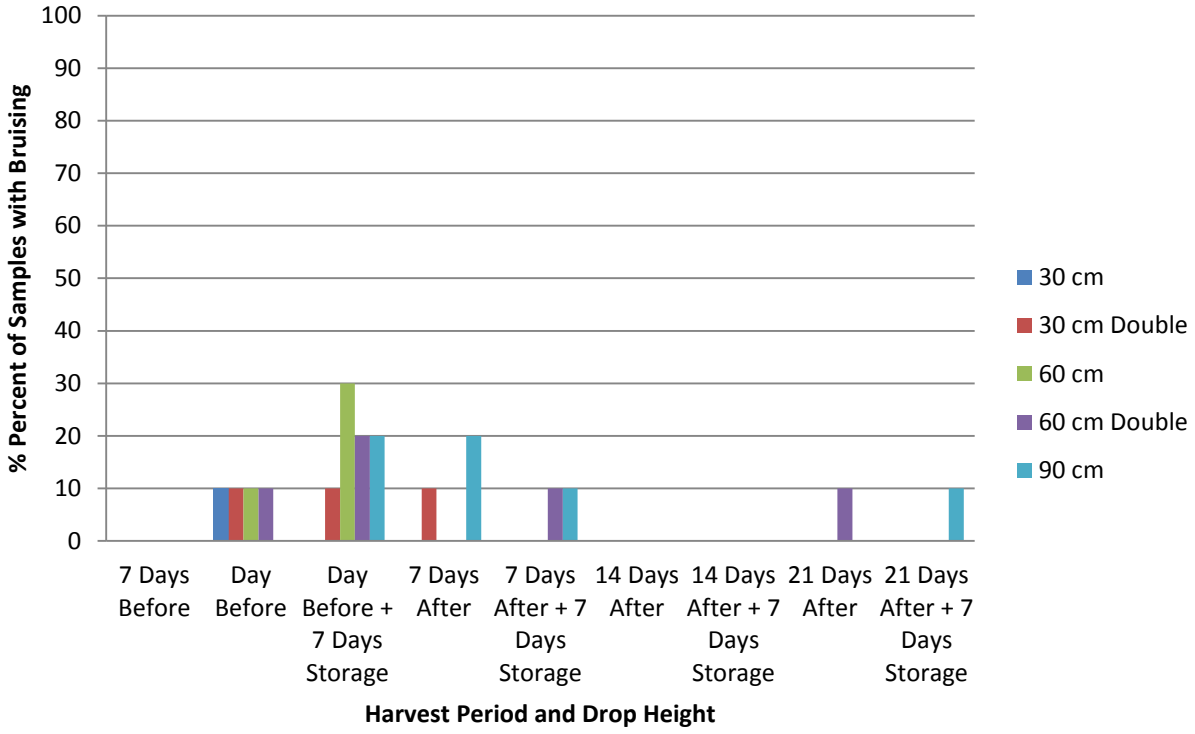

Figure 2-24. 'Red La Soda' Percent of samples with bruising from impact testing (n=10 per category).

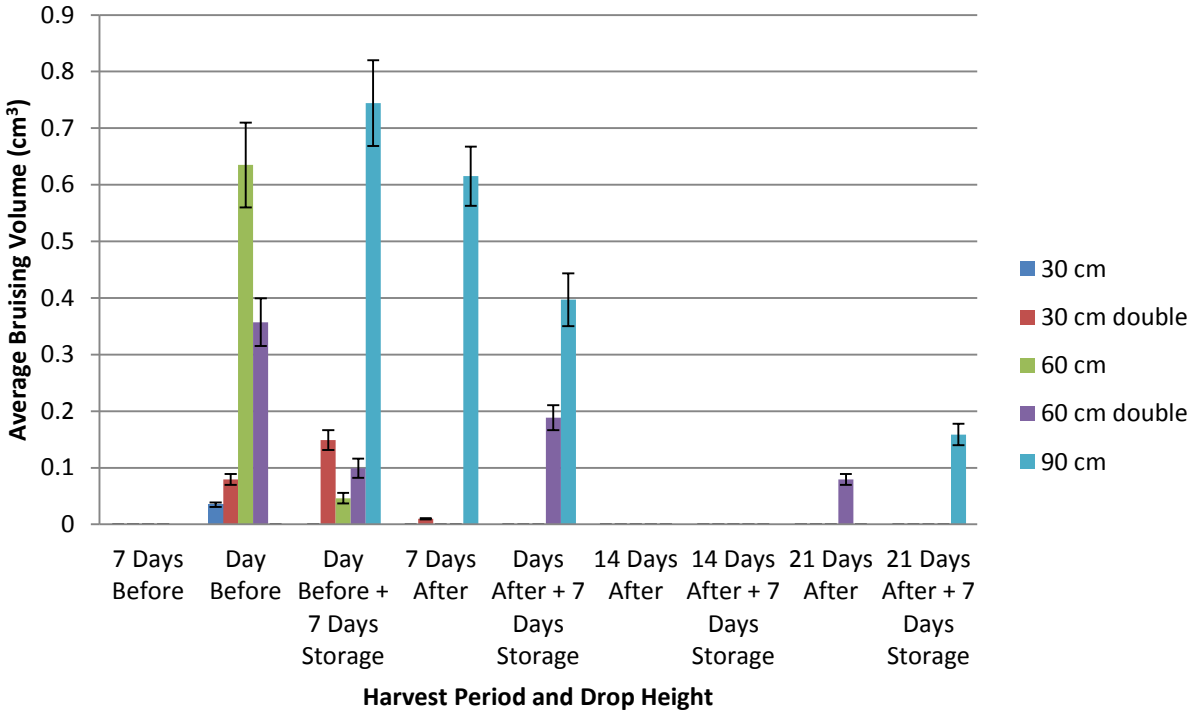

Figure 2-25. 'Red La Soda' Average bruising volume of tubers from impact testing (n=10 per category).

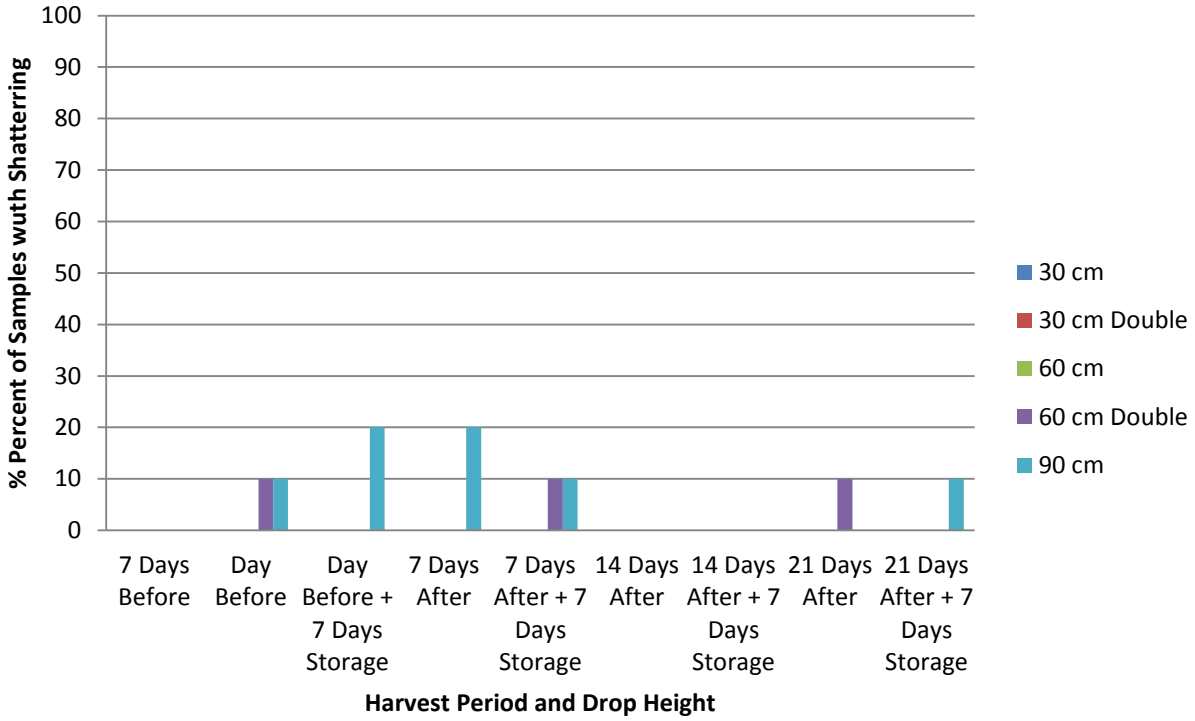

Figure 2-26. 'Red La Soda' Percent of samples with shatter from impact testing (n=10 per category).

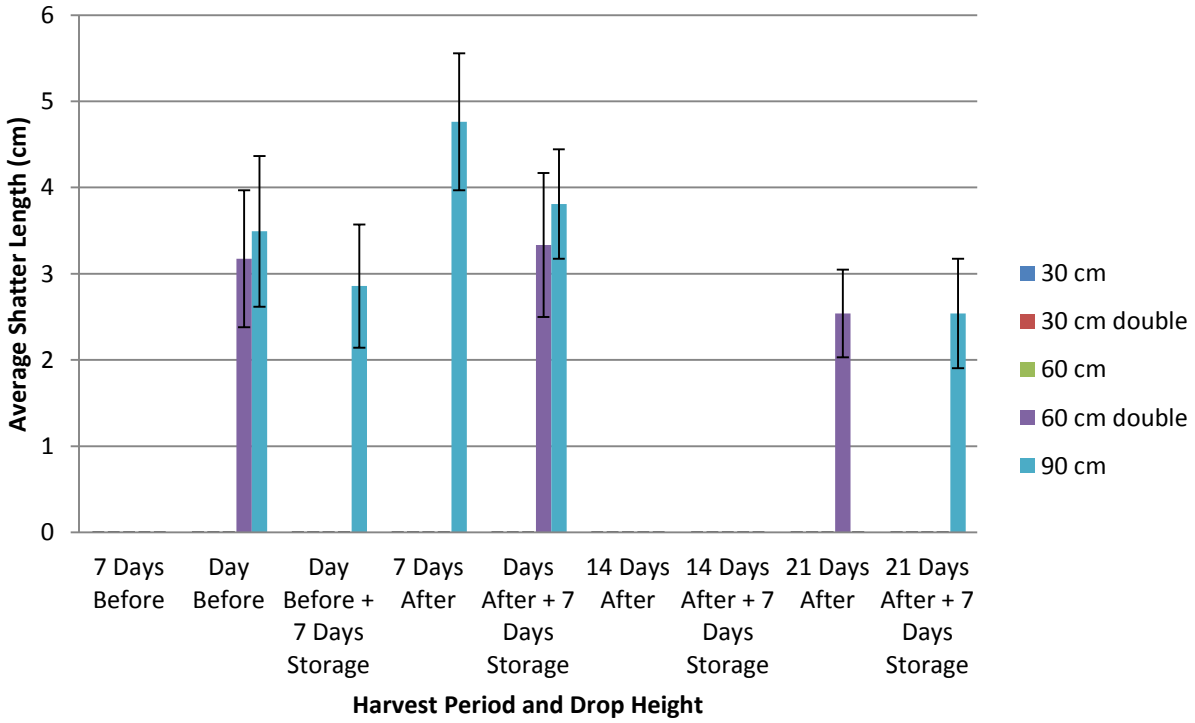

Figure 2-27. 'Red La Soda' Average shatter length of tubers from impact testing (n=10 per category).

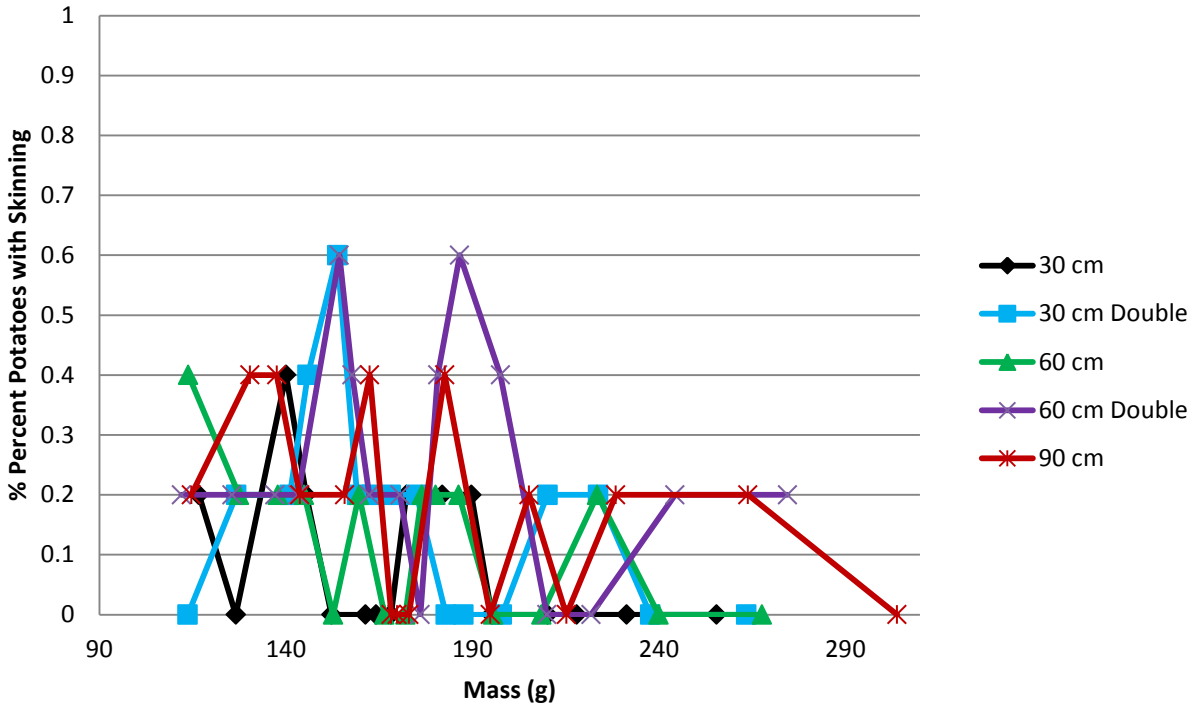

Figure 2-28. 'Red La Soda' Mass of tubers versus percent skinning damage from impact testing (n=70 per category).

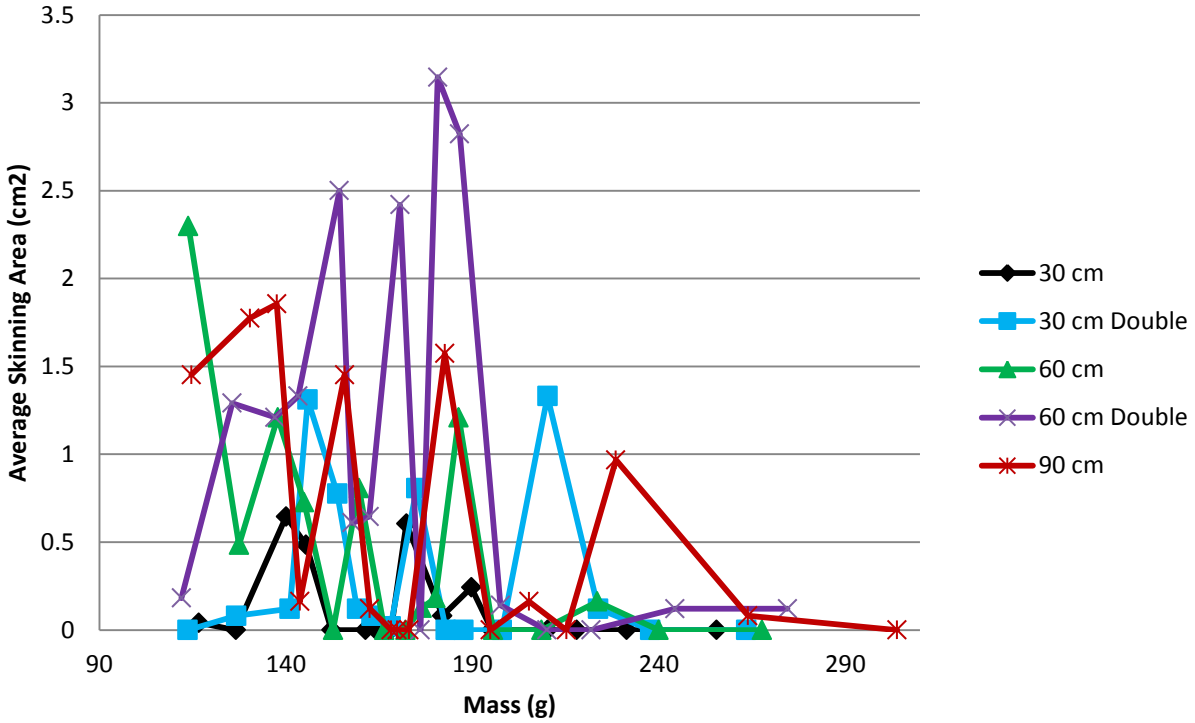

Figure 2-29. 'Red La Soda' Mass of tubers versus average skinning damage area from impact testing (n=70 per category).

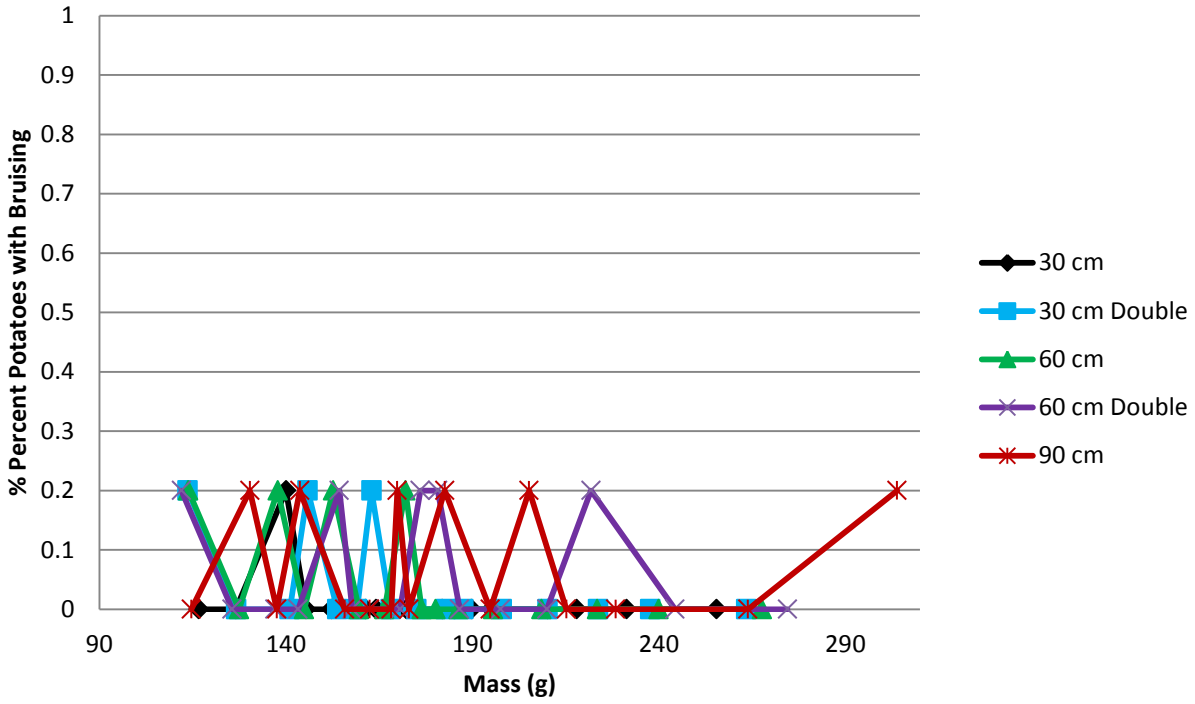

Figure 2-30. 'Red La Soda' Mass of tubers versus percent tubers with bruising damage from impact testing (n=70 per category).

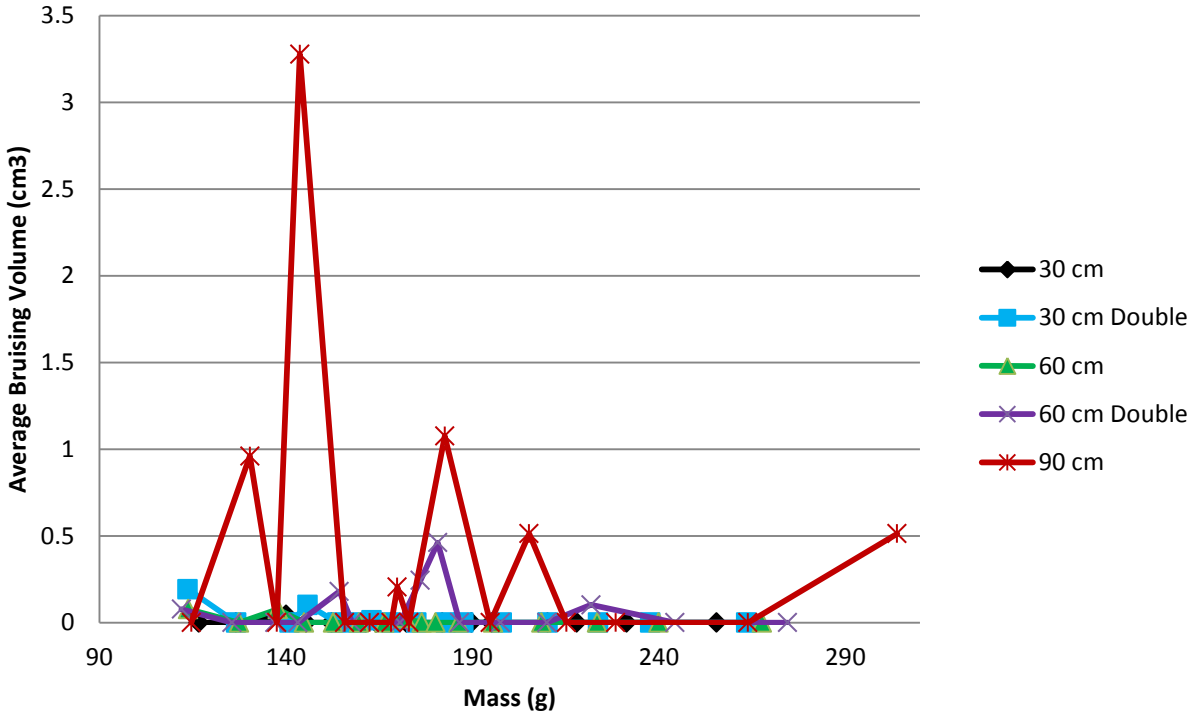

Figure 2-31. 'Red La Soda' Mass of tubers versus average bruising damage volume from impact testing (n=70 per category).

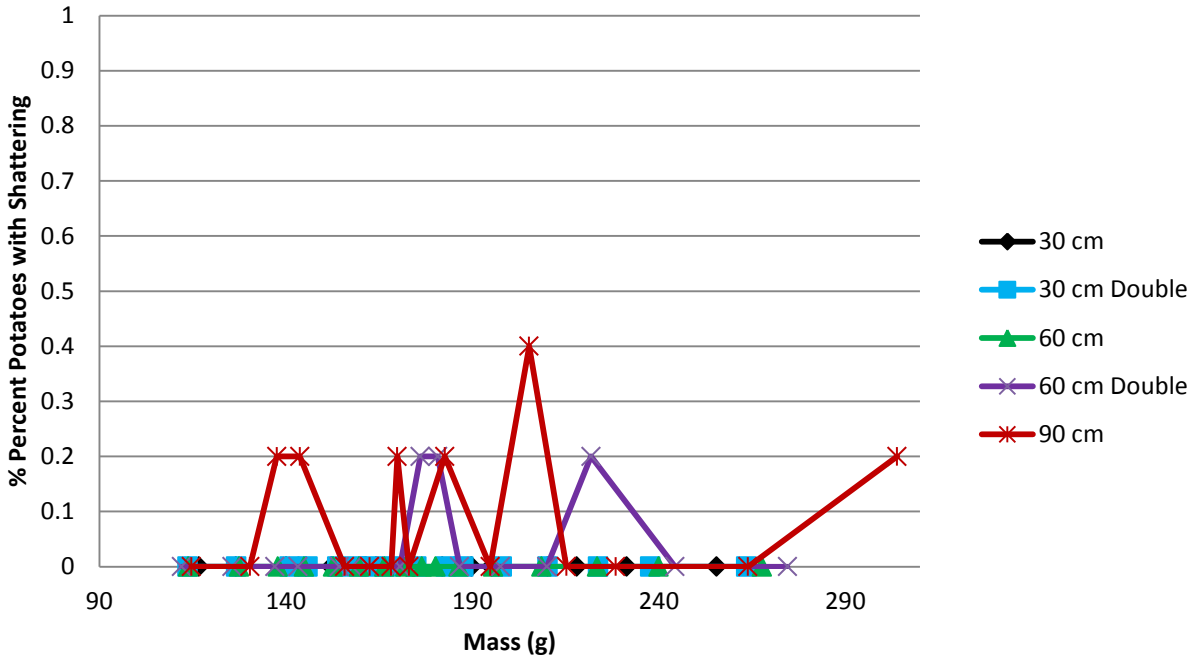

Figure 2-32. 'Red La Soda' Mass of tubers versus percent tubers with shatter damage from impact testing (n=70 per category).

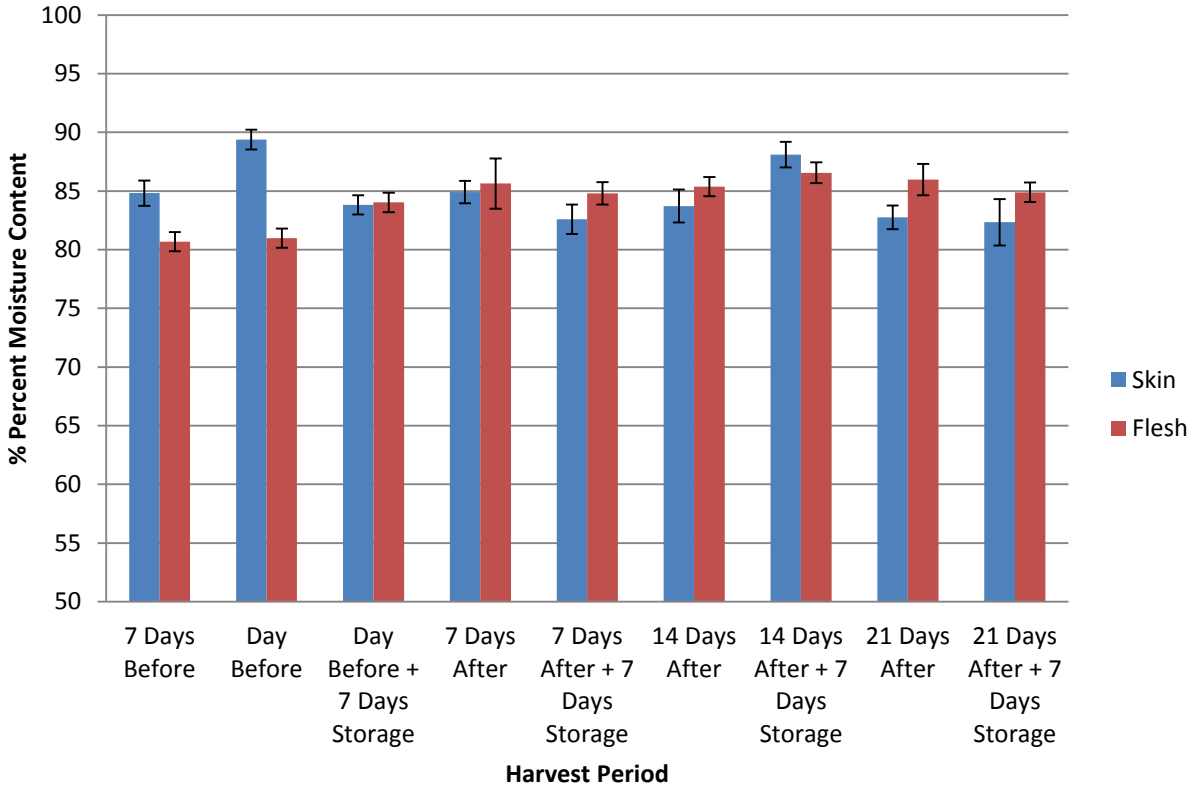

Figure 2-33. 'Fabula' Moisture content levels of skin and flesh at time of impact testing (n=5).

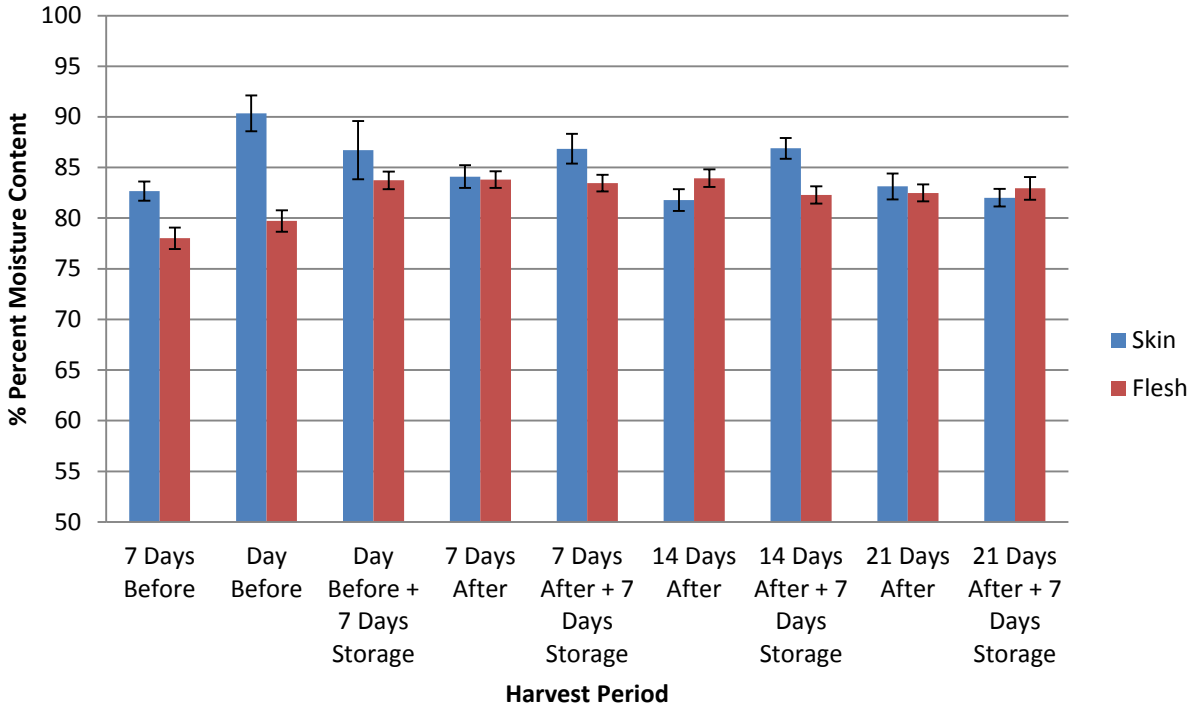

Figure 2-34. 'Red La Soda' Moisture content levels of skin and flesh at time of impact testing (n=5).

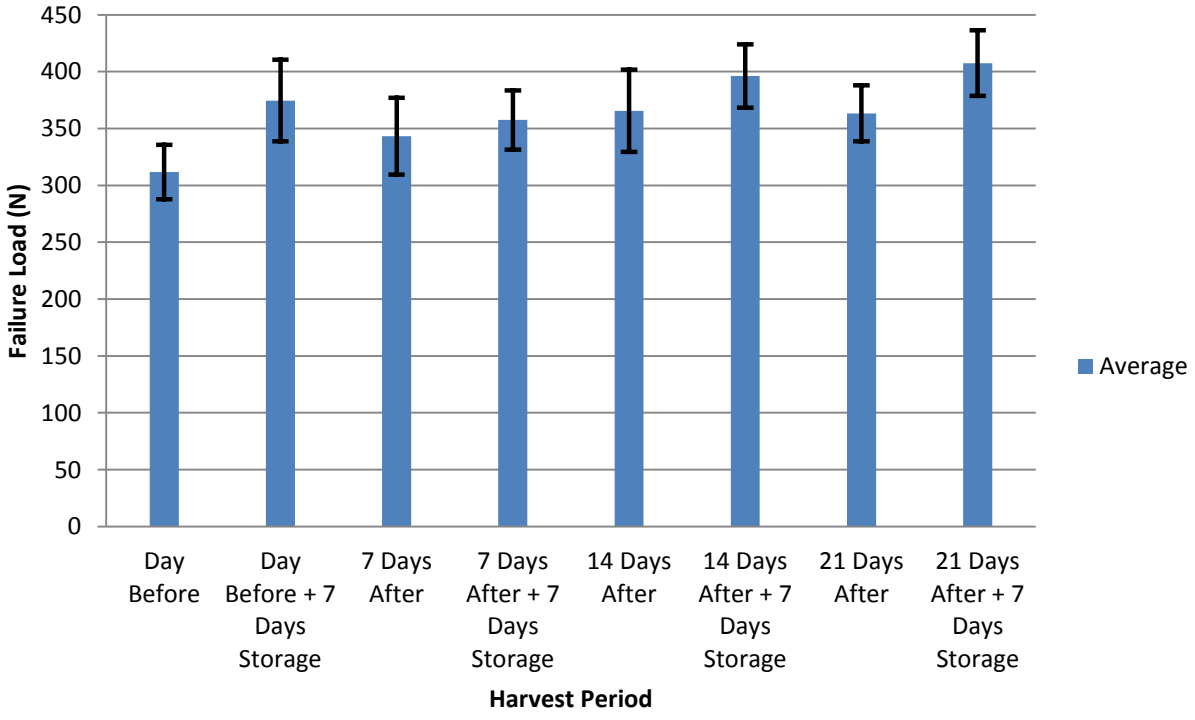

Figure 2-35. 'Fabula' Average compression rupture force failure loading (n=10).

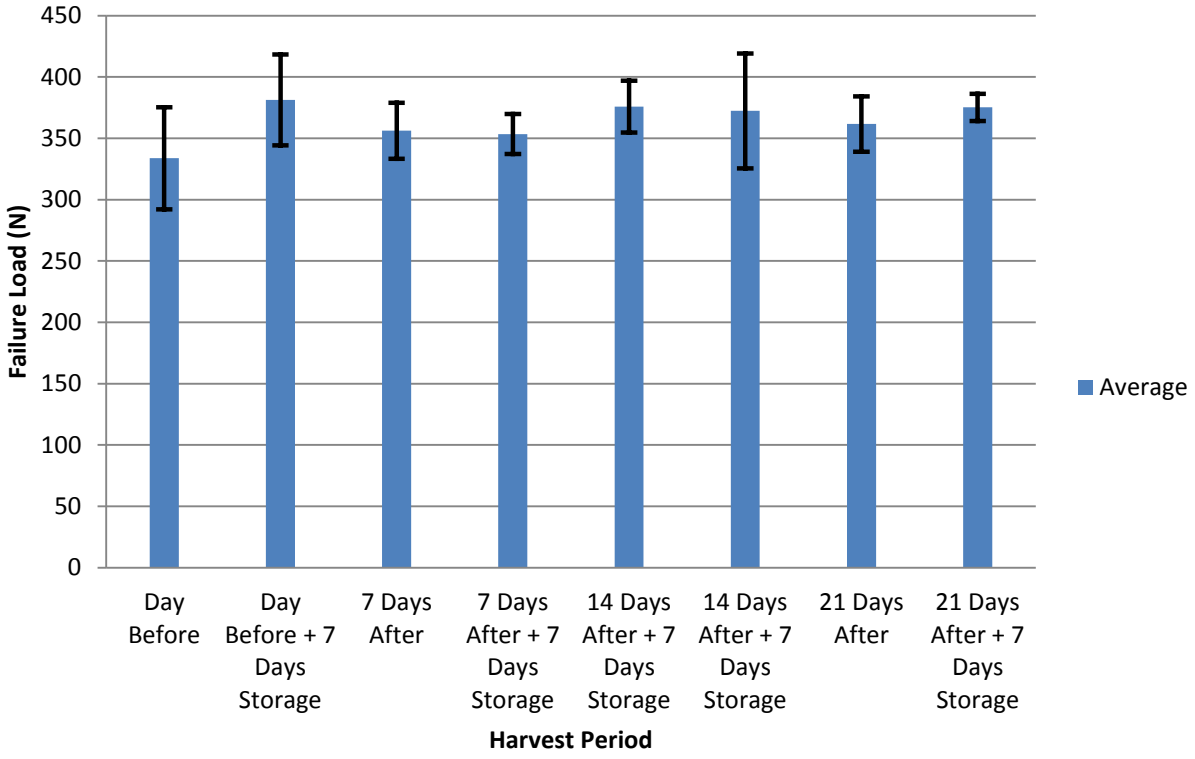

Figure 2-36. 'Red La Soda' Average compression rupture force failure loading (n=10).

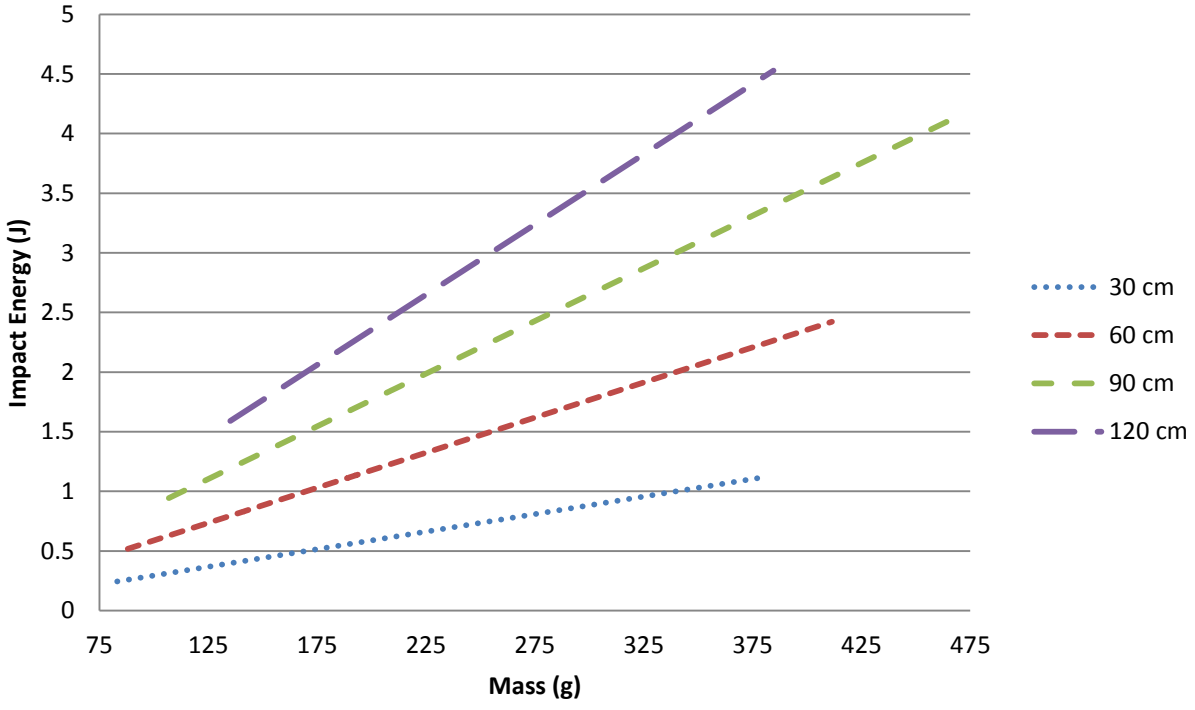

Figure 2-37. Calculated impact energy versus potato mass for drop heights used.

CHAPTER 3
NON-DESTRUCTIVE SPECTRAL MEASUREMENT ASSESSMENT

3.1 Materials and Methods

Visible and near-infrared reflectance technology was utilized in order to collect spectral measurements of damaged, diseased and undamaged potatoes for comparison between the range of 360 and 800 nm. These data were compared in order to locate the differences in spectral measurements between damaged and undamaged potatoes and create calibration models for detecting damage in 'Fabula' and 'Red La Soda' cultivars.

3.1.1 Potato Plant Materials

Sample tubers of two new potato varieties, 'Fabula' and 'Red La Soda,' were hand-harvested on May 13th and 31st, June 7th and 14th, 2011 and July 1st 2012 from the fields of the University of Florida Research and Demonstration Site in Hastings, Florida and were transported to a laboratory at UF in field lugs for data collection (Table 3-1). The variety 'Fabula' had a very high yield and very large size tuber with pale yellow flesh, and oval barrel-shape. It also had an extremely smooth, light yellow-colored skin with shallow eyes. It was described to have good internal bruising resistance, as well as fairly good to very good resistance to many viruses that affect tubers. The other variety 'Red La Soda' had a white to cream colored tuber flesh, a round to oblong shape and smooth deep red colored skin; eyes are of medium to deep depth and well distributed. It was described to have good skinning resistance, good yield potential and a relatively low specific gravity compared to other red-skinned varieties and a general disease resistance requiring standard disease control programs be followed.

Initial sample sets of 40 tubers for each variety were collected for evaluation on May 13th, 2011 in order to determine the effects of moisture content levels on spectral reflectance before testing began on reflectance measurement of damaged samples. Samples for reflectance measurement were collected on May 31st, June 7th and June 14th, 2011 in order to allow potato tubers to naturally change condition after vine-kill for a range of values to be expected at harvests and allow diseases to develop on infected tubers before harvesting and again on July 1st, 2012 in order to increase sample variation for evaluation. The disorders and diseased samples collected included; internal blackspot bruising, shatter, brown rot, greening, sunscald, growth cracking, and insect damage. All samples were collected during late morning to noon hours. Potato tubers were harvested by hand in order to prevent mechanical damage being induced before initial spectral reflectance could be measured in a laboratory.

3.1.2 Mechanical Damage Stimulation and Disorders

In order to provide undamaged potato tuber samples for comparison to mechanical damaged tuber, reflectance measurements were taken before damage was induced in order to provide sample data with 0% damage; mechanical damage was then induced in the group of samples before they were used for measurement and evaluation. Samples of tubers that had disease or disorders were collected in the fields when they were found and sorted into their respective sample groups for each tuber variety.

3.1.2.1 Mechanical damage simulation

Undamaged potato tuber samples for each variety were selected from those harvested in Hastings, Florida. Freshly harvested tubers were mechanically damaged by exposing them to an impact force by means of dropping them from a height of 120 cm, which previous research

showed would cause blackspot bruising (Fig. 3-1 and 2) and/or external shatter (Fig. 3-3 and 4). Once dropped, sample tubers were stored in a 20°C (68°F) and 80% RH cold room for six days in order to allow mechanical damage to develop. After the sixth day, the potato tubers were assessed for external mechanical damages, in order to identify samples with shatter to exclude from internal damage detection measurements and use for external mechanical damage detection with a spectrophotometer (Cary 500, Varian Inc., Palo Alto, CA). External mechanical damage assessment was done visually by looking for skinning and external shatter around the point of impact. Samples with no external evidence of mechanical damage were used for internal mechanical damage detection with the spectrophotometer.

3.1.2.2 Diseases and disorders

Samples of potato tubers with greening, sunscald, brown rot, growth cracking, and insect damage (for 'Red La Soda' only) were collected in the fields at Hastings at the same time as undamaged samples over the weeks and separated into their respective damage categories. These diseases and disorders were previously described (Table 1-3). In addition to field harvested samples of potato tubers with greening, samples were created by leaving undamaged potato tubers exposed to indirect sunlight for 2 weeks in order to allow greening to develop naturally over time (Fig. 3-5 and 6). The number of samples with sunscald naturally increased as time after vine-kill increased, due to unprotected tubers near the surface being exposed to prolonged levels of intense sunlight (Fig. 3-7 and 8). Potato tubers that developed brown rot were limited to those that were exposed to the pathogen before the parent vine was killed and continued to develop the damage related to the disease as harvest weeks went on (Fig. 3-9 and 10). Growth cracking occurred in samples while they were growing and exposed to uneven availability of soil moisture which caused them to split and heal along points of surface tension caused by this occurrence

(Fig. 3-11 and 12). Insect damage only occurred in the fields containing ‘Red La Soda’ tubers, so samples were not available for the ‘Fabula’ variety (Fig. 3-13).

3.1.3 Potato Sampling and Reflectance Measurement

All reflectance measurements were collected using a Cary 500 spectrophotometer (Varian, Inc.) with an integrating sphere from 200 nm to 2500 nm with 1 nm increments as shown in (Fig. 3-14). The spectrophotometer was allowed to warm up for 30 minutes before any samples were taken in order to allow the light source to stabilize. The sample measurement port had a circular area of 1,134 mm^2 with a diameter of 38 mm as shown in (Fig. 3-15). The coating material inside the integrating sphere was white polytetrafluoroethylene (PTFE) which has the capability to diffuse a transmitting light nearly perfectly and maintain optical properties constantly over a wide range of wavelengths from the ultraviolet up to the near infrared range as shown in (Fig. 3-16). UV and mercury lamps were used as light sources. A 50 mm diameter PTFE calibration disk was used to cover the sampling port and obtain the optical reference standard for the system before spectral measurement of samples were made at each sampling period as shown in (Fig. 3-17).

Potato tuber samples for reflectance measurement were collected on May 31st, June 7th and June 14th, 2011. Undamaged potato tubers from each variety were initially measured on each day of harvest in order to create a reference range of data for comparison to samples of damaged, diseased and potato disorders. These potato tuber samples were marked with a 40 mm diameter circle at the point of initial measurement and then damaged at this point to induce mechanical damage development and reflectance measurements were made once again before samples were stored for 6 days to allow damage to develop. Then, samples were separated into groups with

external shatter and no outside visible damage, and reflectance measurements were made for both groups. Once samples with no visible damage were measured, the tubers were sliced along the marked portion where the point of impact occurred. Once sliced, tubers were visually inspected for development of internal blackspot bruising. Blackspot bruising was assessed by determining the percent of the area measured by the 38 mm diameter sampling port that bruising was present to assist in determination of reflectance changes from undamaged samples. This assessment generally required additional cutting of tuber to allow for more accurate measurement.

Samples with disease damage and disorders, which were collected in the fields, were also measured in the spectrophotometer on each day of harvest. However, the additional greening samples which had greening induced on undamaged potato tubers were initially measured and marked with a 40 mm diameter circle at the point of measurement before greening was developed by exposure to sunlight. After greening developed, samples were measured in the spectrophotometer again to allow for comparison of samples before and after greening developed.

Initial samples of ‘Fabula’ for moisture content evaluation were collected on May 13, 2011 in order to determine the effects of moisture content levels on reflectance before testing began on reflectance measurement of damaged and diseased samples. Collected samples were measured for reflectance in the spectrophotometer before evaluations of moisture content levels in the tubers could be determined due to the destructive nature of cutting and drying in the process of determining the moisture content. This was done in order to evaluate the effect of tuber moisture content levels which could influence the results of spectral reflectance among tubers with varying moisture contents. The moisture content levels of agricultural produces were

shown in many studies to affect the reflectance of light for various reasons and spectral ranges. Aluminum sample trays were weighed using an electronic balance (BX 4200H, Shimadzu Corporations, Philippines) before the area of reflectance measurement was cut off and weighed in each sample tray to prepare for dehydrating. Once the samples were collected, they were placed in a hot air drying oven kept at 60°C for 2 weeks to allow for complete removal of moisture. Percent moisture content was calculated by mass for tubers by dividing the initial wet weight minus the final dry weight by initial wet weight and multiplying the result by 100 to get percent.

3.1.4 Determination of Important Wavelengths

The data sample sets for each potato tuber variety and defect were separated and assessed individually on the reflectance values and first derivative using three methods; correlation coefficient (r) spectrum, partial least squares regression and stepwise multiple linear regression.

3.1.4.1 Correlation coefficient spectrum

As previously stated the correlation coefficient spectrum is the simplest method used to determine important wavelengths between spectral reflectance and the desired measurements. The Pearson product-moment correlation coefficient denoted by (r) lies between −1 and 1 with a value of 1 or −1 indicating that the data points have a high linear dependence and a value of 0 indicating that there is no linear correlation between the variables. Correlation coefficients were calculated by using the SAS CORR procedure (SAS, 2009).

3.1.4.2 Partial least squares (PLS) regression

As identified earlier, PLS regression in its simplest form is a linear model that specifies the linear relationship between a dependent response variable Y, and a set of predictor variables X. Wold (1975) initially introduced the analysis tool to the field of chemometrics and it has been spreading to other fields of study ever since. PLS is based on linear transition from a large number of original descriptors to a small number of descriptive factors to provide an optimal model for prediction.

In order to complete the PLS model, the number of factors must be chosen using the Predicted Residual Sum of Squares (PRESS) statistic in PLS. Samples are divided into calibration and validation sets with 2/3 of the samples being used for calibration and 1/3 used for validation. The factors are chosen using cross validation, in which the data sets are divided into two or more groups and this is repeated for each group in order to measure the overall capability of a given form of the model. The PRESS statistic is based on the residuals generated by this process. The optimum number of factors for the PLS models are generally obtained when factors are minimized with a smaller PRESS values indicating better model prediction (Sundberg, 1999). Often selecting the number of factors where the absolute minimum PRESS exists may not be the best choice, since a lower number of factors may have a significantly close PRESS value. Cross validation is a method specified by van der Voet (1994) which uses randomized-based model comparison testing to compare test models with different numbers of extracted factors against the model that minimizes the PRESS. PLS regressions can be calculated by using the SAS PLS procedure with cross validation performed using the CVTEST option in SAS to test the significant differences in the PRESS values (SAS, 2009).

3.1.4.3 Stepwise multiple linear regression (SMLR)

As explained earlier, SMLR starts with no variables in the model and the basic method of obtaining the optimal predictors starts with each *x* variable in the datum set; determining the most highly correlated regression coefficient in the regression model relating to the *y* variable which becomes the first selected variable denoted x_{s1} and the residual sum of squares RSS to assess the correlation of the predictor used in the model. Then regression models with both the pre-selected variable, x_{s1}, and each of the remaining *x* variables are determined using MLR and the corresponding RSS value are calculated for each model. The *x* variable that produces the highest RSS when used in combination with x_{s1} then becomes the second selected variable and is denoted, x_{s2}. This process repeats until the desired number of variables selected by the stepwise regression routine is equal to the desired number of variables as specified by the operator (Yee and Gimel'farb, 1999). SMLR was calculated by using the SAS PROC REG model-selection to perform the stepwise regression method with a threshold value of '0.05' significance to be included in the model, once wavelength selection is unable to find a variable that meets this requirement analysis ends.

3.2 Results and Discussion

3.2.1 Effects of Water on Spectral Characteristics

Moisture content distributions collected for 'Fabula' varied between 78% and 86.6%, while 'Red La Soda' was found to vary between 79% and 92.3% during the course of experiments, which are similar to the skin moisture content previously determined during mechanical damage assessment at 82% to 89% for 'Fabula' and 82% to 90% for 'Red La Soda'. The results for 'Fabula' are similar to results reported by the potato industry and while 'Red La

Soda' had a range that went higher than normal; these results could be due to the potatoes being freshly harvested new potatoes and variation between varieties. The range of water content can range between 73.8% and 81% according to Souci et al. (2000) and Elbatawi et al. (2008) found water content levels from as high as 85% with average water contents around 81.7%. Figure 3-18 shows the spectrum of 'Fabula' potato samples between 200–2500 nm with various moisture contents, while figure 3-19 shows the spectrum of 'Red La Soda' potato samples. Figure 3-20 shows the correlation coefficient of 'Fabula' potato sample reflectance versus moisture content between 200 and 2500 nm, while figure 3-21 shows the correlation coefficient of 'Red La Soda' potato samples.

The reflectance spectrum for 'Fabula' and 'Red La Soda' begins to vary greatly because of the moisture content levels of potato tubers above the 850 nm spectral range, as shown by the extremely high correlation (r) coefficient between moisture and reflectance (Figure 3-20 and 21). The correlation of moisture content for both varieties show results similar to those found by Singh (2005) who determined that the peaks in the wavelength ranges of 738-837, 914-1120, and 1354-1456 nm correspond to the changes of water content in an unknown variety of potato samples. The slight difference in peaks caused by water could be due to the physical characteristics of sample material, which Yee and Gimel'farb (1999) noticed during experimentation and attributed to losses and inefficiencies occurring between molecular interactions and lack of adherence to Hooke's law caused by the physical properties of samples.

The result of moisture content testing versus reflectance spectrums helped influence the decision to run experiments between the range of 360 nm and 800 nm. Moisture content had a reduced secondary effect on the range of wavelengths between 360 nm and 800 nm. This

decision was made in order to avoid errors caused by widely varying moisture contents found naturally in potatoes depending on pre-harvest and post-harvest conditions.

3.2.2 Correlation Coefficient Spectrum

The results for reflectance measurements and correlation coefficients of disorders and diseases (Internal Bruising, Shatter, Greening, Sunscald, Brown Rot, Growth Cracking and Insect Damage) in the spectral range of 360 to 800 nm for the potato varieties ‘Fabula’, ‘Red La Soda’ and a combination of the two varieties (Figure 3-21 thru 3-53). While the sample sizes used in the evaluation of each variety are shown (Table 3-1). Correlation coefficient spectrums for both varieties were created from the correlation between reflectance and the percent of damaged area within the measured dimensions of the tuber for each disorder and disease. The Pearson product-moment correlation coefficient denoted by (r) lies between -1 and 1 with a value of 1 or -1 indicating high linear dependence and a value of 0 indicating that there is no linear correlation between the variables (SAS, 2009). Areas of reflectance for externally visible sample sets were highly correlated with the presence of damage for both varieties and the combination of both, while internal bruising was only slightly correlated for a wide range of wavelengths. However, even the lower correlation coefficient of 0.4 found for internal bruising with combined varieties would be considered significant in the research done by Min et al. (2004) who used correlation coefficients with r larger than 0.3.

Internal bruising coefficients between 360-800 nm for both varieties and combination of the two (Figures 3-24 thru 3-26). For ‘Fabula’ the reflectance between 622-701 nm were the most significantly correlated with $|r|>0.5$, while ‘Red La Soda’ and the combination of both varieties showed the highest correlation above 600 nm up to 800 nm. These results can be

attributed to the melanin development that occurs when sufficient damage causes cellular disruption according to Mathew and Hyde (1997).

Shatter coefficients between 360-800 nm for both varieties and combination of the two (Figures 3-29 thru 3-31). For ‘Fabula’ the reflectance between 360 and 420 nm then 493 and 640 nm were highly correlated with |r| >0.6. ‘Red La Soda’ showed extremely high correlation between 360 and 660 nm with |r|>0.8, while the combination of both showing a reduced correlation of latter between 360 and 660 nm with |r|>0.6. These results can be tied to the similar wavelength reflectance caused by the starch present in the tubers of all varieties.

Greening coefficients between 360-800 nm for both varieties and combination of the two (Figures 3-34 thru 3-36). For ‘Fabula’ the reflectance between 380 and 710 nm were extremely correlated with |r| >0.8. ‘Red La Soda’ showed slight correlation between 510 and 570 nm with |r|>0.4 while samples were extremely correlated between 590 and 700 nm with |r| >0.8. When combining the two varieties the correlation between reflectance and greening was most highly correlated between 400-480 nm and 600-700 nm with |r|>0.6. The reduced significance of greening in ‘Red La Soda’ samples could be due to the skin of the tubers being a deep reddish color which could already have some greens and other pigments associated with it naturally in the 546 nm range, while ‘Fabula’ which has a dull yellow coloration has no pigments close to those reflected by chlorophyll which causes the greening.

Sunscald coefficients between 360-800 nm for both varieties and combination of the two (Figures 3-39 thru 3-41). For ‘Fabula’ the reflectance between 490 and 700 nm were extremely correlated with |r|>0.8. ‘Red La Soda’ showed high correlation between 360- 480 nm and 620-710 nm with |r| >0.6, while the combination of both varieties showed slightly reduced correlation

between the same wavelengths as ‘Red La Soda’ with |r|>0.5. These changes in wavelength reflection are associated with the burning of pigments in the tubers which causes yellow and brownish coloration in the tubers.

Brown rot coefficients between 360-800 nm for both varieties and combination of the two (Figures 3-44 thru 3-46). ‘Fabula’ and ‘Red La Soda’ showed reflectance between 360 and 800 nm that were extremely correlated around |r| >0.8. A combination of both varieties had a reduction in correlation between the wavelengths 360-600 nm with |r|<0.7, while the rest of the spectrum stayed above |r|>0.8. These results could mean that the main pigment formation caused by brown rot lies above the 600 nm range and the variety ‘Red La Soda’ has a very pigments present in the 360-600 nm range which separate it from ‘Fabula’.

Growth cracking coefficients between 360-800 nm for both varieties and combination of the two (Figures 3-49 thru 3-51). For ‘Fabula’ the reflectance between 360 and 800 nm were extremely correlated with |r| >0.8. While ‘Red La Soda’ and a combination of both varieties once again had reflectance between 360-460 nm and 620-800 nm extremely correlated with |r| >0.6. These results are due to the difference in cracking growth between ‘Fabula’ and ‘Red La Soda’. While cracking ‘Fabula’ forms a light brown scar in the affected area, while ‘Red La Soda’ exhibits a stretching appearance and less extreme scarring formation.

Insect damage coefficients lie between 360-800 nm for ‘Red La Soda’ (Figure 3-53). The results show a reflectance between 360-480 nm and 640-800 nm extremely correlated with |r| >0.8. These results show a significant correlation range similar to those for sunscald and growth cracking, which could make differentiating between the three types of damage difficult.

Each set of data for ‘Fabula’ potato disorders has a range of values between 360 nm and 800 nm with a |r| value greater than 0.4; these results display that there is a correlation between wavelength values and percent area damaged being scanned which be used to calibrate a model in order to predict damage.

3.2.3 Partial Least Squares (PLS) Regression

In order to complete the PLS model, the number of factors must be chosen using the Predicted Residual Sum of Squares (PRESS) statistic in PLS, predictive modeling using cross validation and minimizing the error of the prediction model by checking how the number of factors affects the results. Sundberg (1999) states that the optimal number of factors for PRESS is generally obtained when factors are minimized and smaller PRESS sizes usually develop better fit to data.

Results of PLS analysis for ‘Fabula’ (Table 3-2), ‘Red La Soda’ (Table 3-3), and a combination of both varieties (Table 3-4). The tables depict the extracted factors, dependent variables, PRESS, SEC, SEP, RPD and RMSD for selected factor values of each varieties disorder sample set. The regression relationship between predicted damage values versus actual damage values for the number of factors chosen for each variety and the combination of both sample sets using reflectance and 1st derivative evaluation, as well as the B-coefficients determined for each wavelength using PLS in order to show the most significant wavelengths from the reflectance spectrum measured (Figures 3-54 thru 98).

Prediction models for internal bruising of ‘Fabula’, ‘Red La Soda’ and the combination of both (Figures 3-54 thru 3-60) had relatively low wavelength selection variation with R^2 higher than 0.96 for all prediction models using a various number of extracted factors which would

always favor 1st derivative prediction using fewer factors in all situations. For 'Fabula' the smallest error was at 15 factors and obtained a SEP of 0.991% with standard wavelengths, while 1st derivative results were able to use five factors to obtain a SEP of 0.706%. 'Red La Soda' only needed 11 factors to obtain a SEP of 1.245% with standard wavelengths, while 1st derivative results only needed four factors in order to obtain a SEP of 0.960%. Combining the two varieties resulted in an increase of prediction error by increasing the SEP to 2.847% with 15 factors used, while 1st derivative SEP was reduced to 1.487% with seven factors. For internal bruising prediction of each variety the most prediction error occurred in samples with no damage at all, while combining them resulted in error in prediction as high as 9% in healthy samples and varying error in damaged samples.

Internal bruising which was associated with the production of melanin had its highest B-coefficients calculated by the PLS procedure for 'Fabula' with 15 factors at 799, 795, 787, 768, 735, 732, 714, 709, 692, 464, 425, 400, 394, 390, 384, 374, 373, 371 and 365 nm; while 1st derivative results with five factors were 790, 730, 666, 650, 605, and 530 nm. For 'Red La Soda' with 11 factors they were 371, 363, 365, 370, 380, 390, 397, 714, 766, 782, 790, 770 and 787 nm; while 1st derivative results with four factors were 683, 687, 588, 566, 462, 465 and782 nm. For the combination of varieties with 15 factors they were 793, 790, 782, 762, 752, 747, 710, 392, 383, 378, 372, 373 and 370 nm; while 1st derivative results with seven factors were 728, 709, 793, 787, 676, 660, 420 and 400 nm. This shows that the most important wavelengths for model prediction were in the same general area for both varieties.

Prediction models for shatter of 'Fabula', 'Red La Soda' and the combination of both (Figures 3-61 thru 3-67) had relatively low wavelength selection variation with R^2 higher than 0.97 for all prediction models using a various number of extracted factors which would always

favor 1st derivative prediction using fewer factors in all situations. For 'Fabula' the smallest error was obtained with four factors at a SEP of 1.239 % with standard wavelengths, while 1st derivative results were able to use two factors to obtain a SEP of 0.696%. 'Red La Soda' only needed four factors to obtain a SEP of 0.936 % with standard wavelengths, while 1st derivative results only needed two factors in order to obtain a SEP of 1.261%. Combining the two varieties resulted in an increase of prediction error by increasing the SEP to 1.678% with five factors used, while 1st derivative SEP results were 1.783% with two factors. For shatter prediction the most prediction error occurred in samples with no damage or very high damage with error in prediction as high as 15% for extremely damage samples for combined spectral data of the two varieties.

Shatter wavelengths were the result of missing skin surface area and increased reflectance from potato starch. The highest B-coefficients calculated by the PLS procedure for 'Fabula' with four factors were between 500-516, 475-486, 445-455, 360-400 nm; while 1st derivative results with two factors were between 360-371, 380-425, 436-448, 455-465, 470-480 and 482-510 nm. For 'Red La Soda' with four factors they were between 360-384, 423-462 and 514-579 nm; while 1st derivative results with two factors were between 360-371, 397-405, 427-436, 470-480 and 488-520 nm. For the combination of varieties with five factors they were 360-397, 440-460 and 473-484 nm; while 1st derivative results with two factors were 768, 752, 722, 713, 540, 449-466 and 553 nm. This shows that the most important wavelengths for model prediction were in the same general area for both varieties.

Prediction models for greening of 'Fabula', 'Red La Soda' and the combination of both (Figures 3-68 thru 3-74) had relatively low wavelength selection variation with R^2 higher than 0.98 for all prediction models using a various number of extracted factors which would always

favor 1st derivative prediction using fewer factors in all situations. For 'Fabula' the smallest error was at seven factors with a SEP of 0.017% for standard wavelengths, while 1st derivative results were able to use two factors to obtain a SEP of 0.285%. 'Red La Soda' only needed five factors to obtain a SEP of 1.881% with standard wavelengths, while 1st derivative results only needed two factors in order to obtain a SEP of 0.771%. Combining the two varieties resulted in an increase in factors by requiring seven to get an SEP of 1.511%, while 1st derivative improved SEP results to 1.003% with three factors. For greening prediction there was almost no error at all in the prediction model due to the easily detected increase in chlorophyll which affected the wavelength reflectance.

Greening wavelength changes were associated with the increase in chlorophyll, solanine and other photosynthesis chemicals. The highest B-coefficients calculated by the PLS procedure for 'Fabula' with seven factors were 800, 774, 767, 762, 760, 384, 379, 371 and 360 nm; while 1st derivative results with two factors were 767, 768, 758, 748, 722, 670, 530, 506, 478, 463 and 440 nm. For 'Red La Soda' with five factors they were between 618-698 nm; while 1st derivative results with two factors were between 680-715, 725, 735, 744, 750, 797, 530, 497, 480, 475, 463 and 461 nm. For the combination of varieties with seven factors they were between 670-683 nm; while 1st derivative results with three factors were 725, 748, 798, 473, 442, 406 and 397 nm. This shows that the most important wavelengths for model prediction were the ones that contributed more information in 'Fabula'.

Prediction models for sunscald of 'Fabula', 'Red La Soda' and the combination of both (Figures 3-75 thru 3-81) had relatively low wavelength selection variation with R^2 higher than 0.97 for all prediction models using a various number of extracted factors which would always favor 1st derivative prediction using fewer factors in all situations. For 'Fabula' error was

minimized at eight factors in order to obtain a SEP of 1.154% with standard wavelengths, while 1st derivative results were able to use four factors to obtain a SEP of 0.598%. 'Red La Soda' needed nine factors to obtain a SEP of 1.4 % with standard wavelengths, while 1st derivative results only needed three factors in order to obtain a SEP of 0.957%. Combining the two varieties resulted in an increase in factors by requiring 15 to get an SEP of 2.028%, while 1st derivative improved SEP results to 1.476% with six factors. For sunscald prediction the most prediction error occurred once again in samples with no damage at all which resulted in error in prediction as high as 10% with combined spectral data of the two varieties.

Sunscald was the burning of potato surface area by exposure to high temperatures and sun light. The highest B-coefficients calculated by the PLS procedure for 'Fabula' with eight factors were between 798-788, 785, 780, 777, 397, 371, 365-362 nm; while 1st derivative results with four factors were 798, 797, 788, 787, 780, 748, 726, 722, 718, 711, 682, 610, 606, 600 and 599 nm. For 'Red La Soda' with nine factors they were 800, 799, 686, 683, 650, 644, 366, 363 and 360 nm; while 1st derivative results with three factors were 725, 711, 687, 540, 527 and 512 nm. For the combination of varieties with 15 factors they were 800, 792, 788, 780, 770, 766, 764, 746 and 722 nm; while 1st derivative results with six factors were 797, 790, 788, 777, 774, 750, 720, 713, 708 and 680 nm. This shows that the most important wavelengths for model prediction were in the same general area for both varieties.

Prediction models for brown rot of 'Fabula', 'Red La Soda' and the combination of both (Figures 3-82 thru 3-88) had relatively low wavelength selection variation with R^2 higher than 0.98 for all prediction models using a various number of extracted factors which would always favor 1st derivative prediction using fewer factors in all situations. 'Fabula' only needed eight factors to minimize error with a SEP of 1.34% with standard wavelengths, while 1st derivative

results were able to use three factors to obtain a SEP of 0.745%. ‘Red La Soda’ needed 10 factors to obtain a SEP of 1.267% with standard wavelengths, while 1st derivative results only needed four factors in order to obtain a SEP of 0.822%. Combining the two varieties resulted in an increase in factors by requiring 15 to get an SEP of 1.878%, while 1st derivative SEP results were 2.314% with four factors. For brown rot prediction the error was evenly distributed for the two varieties, but combining them caused prediction error focused around samples with no damage which was likely caused by the differences between the skin coloration of the varieties.

Brown rot caused by the bacterium *Ralstonia solanacearum* causes tuber flesh to rot and turn a brownish-grey color which resulted in the highest B-coefficients calculated by the PLS procedure for ‘Fabula’ with eight factors between 370-375, 366 and 365 nm; while 1st derivative results with three factors were 787, 725, 676, 677, 646, 608, 607, 594, 589, 576, 566, 533, 470 and 440 nm. For ‘Red La Soda’ with 10 factors they were 800, 787, 416, 384, 382, 378 and 361 nm; while 1st derivative results with four factors were 799, 791, 790, 777, 774, 736, 726, 713, 709, 688, 673, 670, 657, 533 and 507 nm. For the combination of varieties with 15 factors they were 793, 790, 782, 762, 747, 383, 392, 372, 373 and 370 nm; while 1st derivative results with seven factors were 797, 790, 683, 660, 530, and 423 nm. This shows that the most important wavelengths for model prediction were in the same general area for both varieties.

Prediction models for growth cracking of ‘Fabula’, ‘Red La Soda’ and the combination of both (Figures 3-89 thru 3-95) had relatively low wavelength selection variation with R^2 higher than 0.97 for all prediction models using a various number of extracted factors which would always favor 1st derivative prediction using fewer factors in all situations. ‘Fabula’ used nine factors to minimized error at a SEP of 2.086% with standard wavelengths, while 1st derivative results were able to use four factors to obtain a SEP of 0.748%. ‘Red La Soda’ needed 11 factors

to obtain a SEP of 2.120% with standard wavelengths, while 1st derivative results only needed five factors in order to obtain a SEP of 1.071%. Combining the two varieties resulted in an increase in factors by requiring 15 to get an SEP of 3.039%, while 1st derivative improved the SEP results to 1.949% with six factors. For growth cracking prediction the error was evenly distributed for the two varieties, but combining them caused prediction error of up to 15% focused around samples with no damage which was likely caused by the differences between the cracking developments of the two varieties.

Growth cracking which was the result of tuber suberization to repair splitting during growth had its highest B-coefficients calculated by the PLS procedure for 'Fabula' with nine factors at 361, 363, 366, 371, 373, 382, 390, 394, 787, 790 and 795 nm; while 1st derivative results with four factors were 790, 787, 756, 733, 729, 722, 711, 677, 645, 643, 631, 602, 536, 438 and 473 nm. For 'Red La Soda' with 11 factors they were 790, 791, 777, 754, 746, 750, 722, 713, 685, 662, 566, 533, 516, 458 and 402 nm; while 1st derivative results with five factors were 622, 433, 625 and 633 nm. For the combination of varieties with 15 factors they were 800, 797, 789,787, 782, 778, 752, 738, 734, 722, 704, 404, 398, 380, 378 nm; while 1st derivative results with six factors were 789, 787, 753, 730, 686, 665, 579, 540, 475, 442, 413 and 371 nm. This shows that the most important wavelengths for model prediction were in the same general area for both varieties.

Prediction models for insect damage of 'Red La Soda' (Figures 3-96 thru 3-98), which had relatively low wavelength selection variation with R^2 higher than 0.99 for all prediction models using a various number of extracted factors which would always favor 1st derivative prediction using fewer factors in all situations. 'Red La Soda' minimized error using 12 factors to obtain a SEP of 1.216% with standard wavelengths, while 1st derivative results only needed

three factors in order to obtain a SEP of 0.988%. For insect damage prediction the error was evenly distributed due to low sample numbers which were primarily extremely damaged.

Insect damage which was the result of tuber suberization from tuber matter being eaten; had its highest B-coefficients calculated by the PLS procedure for 'Red La Soda' with 12 factors at 800, 797, 792, 787, 783, 777, 750, 527, 507, 465, 380, 376, 375, 371 and 363 nm; while 1st derivative results with three factors were 793, 787, 770, 740, 738, 700, 690, 670, 657, 580, 574, 568, 519, 512, 502, 436 and 420 nm.

Since all sample disorders had significant wavelengths with a high B-coefficient value between the rand of 360-460 and/or 700-800 spectral wavelength scans could be concentrated on these areas in order to calibrate models for prediction of damage faster on a packaging line. Similarly, Xing et al. (2005) observed pronounced spectral changes for apples containing the internal browning disorder 'brown heart' in the range of 700-900 nm.

3.2.4 Stepwise Multiple Linear Regression (SMLR)

SMLR was used as a second method of wavelength significance examination. The results of statistical analysis for SMLR are listed for 'Fabula' (Table 3-5), 'Red La Soda' (Table 3-6) and the combination of both varieties (Table 3-7). The stepwise option of SAS selected the most highly correlated wavelengths for each 'Fabula' sample set until the accuracy of new wavelengths gave diminishing returns below a threshold significance of 0.05. Prediction models of SMLR for 'Fabula', 'Red La Soda' and combined show the accuracy of model calculations (Figure 3-99 thru 3-117).

Stepwise selection picked three wavelengths to predict 'Fabula' internal bruising, the selected wavelengths 795, 791, and 435 nm resulted in a selection variation R^2 of 0.9202.

Stepwise selection picked six wavelengths to predict 'Fabula' internal bruising 1st derivative, the selected wavelengths 408, 742, 531, 456, 482, and 435 nm resulting in a R^2 of 0.9986. 'Red La Soda' used the five wavelengths 774, 776, 763, 788 and 784 nm to produce a variation R^2 of 0.9824; while the 1st derivative used eight wavelengths 640, 412, 705, 648, 650, 786, 781 and 484 nm for a R^2 of 1. Combining the two varieties resulted in a wavelength selection of no significant variables that met the 0.05 threshold; while 1st derivative results selected 10 wavelengths 682, 667, 716, 427, 589, 558, 791, 576, 540 and 443 nm for a R^2 of 0.9711. Although 'Fabula' and 'Red La Soda' had selected wavelengths close to each other, 795 and 791 versus 788 and 784, combining the two varieties internal bruising data failed to give results with enough significance to include. Using the 1st derivative however, resulted in wavelengths near the previously individually selected wavelengths being used.

Stepwise selection picked eight wavelengths to predict 'Fabula' shatter, the wavelengths selected were 432, 438, 383, 379, 382, 386, 376 and 471 nm for a R^2 of 0.9996; the 1st derivative selection of wavelength chose 11 which were 499, 500, 629, 504, 688, 613, 722, 790 690, 648 and 654 nm for a R^2 of 1. 'Red La Soda' used the five wavelengths 568, 398, 588, 403 and 514 nm to produce a variation R^2 of 0.9999; while the 1st derivative used nine wavelengths 502, 625, 788, 576, 585, 471, 642, 621 and 479 nm for a R^2 of 0.9999. Combining the two varieties resulted in the selection of the five wavelengths 378, 362, 388, 395 and 422 nm for a R^2 of 0.9945; while 1st derivative results selected 14 wavelengths 672, 388, 390, 437, 582, 365, 366, 451, 387, 703, 570, 541, 649 and 733 nm for a R^2 of 0.9988. Combining the shatter data for both varieties resulted in a selection of wavelengths which appeared to be more influenced by the results found using 'Fabula' alone, while 1st derivative results were equally influenced to the wavelength selection of both varieties being in the same general area.

Stepwise selection picked two wavelengths to predict 'Fabula' greening, the selected wavelength 702 and 503 nm resulted in a R^2 of 0.9932. Stepwise selection picked four wavelengths to predict 1st derivative, the selected wavelengths 688, 510, 533 and 625 nm resulting in a R^2 of 1. 'Red La Soda' used the two wavelengths 680 and 698 nm to produce a variation R^2 of 0.9978; while the 1st derivative used four wavelengths 650, 391, 673 and 730 nm for a R^2 of 0.9999. Combining the two varieties resulted in the selection of the three wavelengths 681, 672 and 517 nm for a R^2 of 0.9927; while 1st derivative results selected 10 wavelengths 697, 758, 578, 763, 363, 711, 738, 405, 747 and 562 nm for a R^2 of 0.9999. Combining greening data resulted in wavelength selection in the general area of those selected separately, while 1st derivative selection chose many wavelengths near those selected for 'Red La Soda'.

Stepwise selection picked two wavelengths to predict 'Fabula' sunscald; the selected wavelength 446 and 432 resulted in a R^2 of 0.979. Stepwise selection picked six wavelengths to predict 'Fabula' sunscald 1st derivative, the selected wavelengths 518, 792, 625, 421, 650 and 543 nm resulting in a R^2 of 1. 'Red La Soda' used the two wavelengths 435 and 433 nm to produce a variation R^2 of 0.9852; while the 1st derivative used six wavelengths 750, 608, 425, 530, 444 and 675 nm for a R^2 of 1. Combining the two varieties resulted in the selection of the seven wavelengths 786, 773, 589, 588, 629, 787 and 758 nm for a R^2 of 0.9968; while 1st derivative results selected six wavelengths 729, 430, 483, 433, 428 and 553 nm for a R^2 of 0.9932. Combining the sunscald data resulted in wavelength selection which varied greatly from those selected for both varieties separately, which were both between 446 and 432 nm. Combined 1st derivative wavelength selection matched both varieties very closely.

Stepwise selection picked two wavelengths to predict 'Fabula' brown rot; the selected wavelength 689 and 688 nm resulted in a R^2 of 0.9969. Stepwise selection picked six

wavelengths to predict ‘Fabula’ brown rot 1st derivative, the selected wavelengths 518, 792, 625, 421, 650 and 543 nm resulting in a R^2 of 1. ‘Red La Soda’ used the two wavelengths 665 and 607 nm to produce a variation R^2 of 0.9824; while the 1st derivative used six wavelengths 631, 781, 776, 629, 442 and 615 nm for a R^2 of 0.9996. Combining the two varieties resulted in the selection of the three wavelengths 708, 487 and 712 nm for a R^2 of 0.9931; while 1st derivative results selected 15 wavelengths 567, 579, 433, 662, 717, 759, 405, 439, 737, 671, 434, 718, 390, 482 and 689 nm for a R^2 of 0.9999. Combing the data for brown rot resulted in very different results from those found for ‘Red La Soda’; 1st derivative selection however resulted in a wide selection of wavelengths that were close to some of the results for both varieties.

Stepwise selection picked seven wavelengths to predict ‘Fabula’ growth cracking, the selected wavelengths 545, 516, 517, 547, 477, 543 and 486 nm resulting in a R^2 of 0.9995. Stepwise selection picked six wavelengths to predict ‘Fabula’ growth cracking 1st derivative, the selected wavelengths 510, 769, 528, 453, 529 and 473 nm resulting in a R^2 of 0.9996. ‘Red La Soda’ used one wavelength 381 nm to produce a variation R^2 of 0.8793; while the 1st derivative used four wavelengths 622, 433, 625 and 633 nm for a R^2 of 0.9978. Combining the two varieties resulted in the selection of the six wavelengths 670, 461, 673, 400, 401 and 669 nm for a R^2 of 0.9906; while 1st derivative results selected 18 wavelengths 475, 460, 651, 520, 440, 603, 579, 459, 427, 770, 685, 638, 387, 512, 381, 479, 556 and 800 nm for a R^2 of 1. Combining data for growth cracking resulted in wavelength selection that was not similar to either variety, while 1st derivative selection chose wavelengths across the spectrum.

Stepwise selection picked one wavelength to predict ‘Red La Soda’ insect damage; the selected wavelength 800 nm resulted in a R^2 of 0.8891. Stepwise selection picked two

wavelengths to predict 1st derivative, the selected wavelengths 549 and 586 nm resulting in a R^2 of 1.

3.3 Summary

This chapter was focused on the objective to determine important wavelengths in the electromagnetic spectrum that could help develop a real-time damage sensor for the potato varieties 'Fabula' and 'Red La Soda' in the future. Reflectance of 'Fabula' potato samples were measured from 200 nm to 2500 nm using a spectrophotometer in a laboratory environment in order to determine the effects of moisture content on the reflectance found in tubers. While examining results, the reflectance spectrum for 'Fabula' was found to be greatly influenced by moisture content levels above 900 nm; this was similar to results found by Yee and Gimel'farb (1999), where they discovered evidence for 5 maximum wavelengths between 700-2500 nm (at 760, 970, 1190, 1450 and 1940 nm) which were heavily influenced by moisture content in organic samples and stated that physical properties of organic samples could influence the location of moisture content wavelength peaks. Bull (1991) suggests that if reference wavelengths are sensitive to the moisture content of the sample that calibration may become linear over a relatively small range of moisture contents and states it is preferable to choose reference wavelengths for which reflectance is relatively insensitive to moisture content. These results which naturally varied between 78% and 92.3% moisture content across the two varieties 'Fabula' and 'Red La Soda' combined with the cost of spectrometers which would be less expensive for packing house purposes led to the decision to use the range of the electromagnetic spectrum from 360 nm to 800 nm for disorder detection in potato tuber samples.

The reflectance of ‘Fabula’ and ‘Red La Soda’ samples were measured from 360 nm to 800 nm with a spectrophotometer in a laboratory environment. A correlation coefficient spectrum, PLS regression and SMLR procedures were then used to determine important wavelengths for detecting; while PLS was also used for prediction of percent damage present in samples. PLS regression yielded good results, while SMLR and correlation coefficient gave alternative information into the significance of some wavelength ranges in damage detection (Tables 3-8 thru 3-10).

For internal bruising, both varieties showed significant correlation coefficient above 0.4 between 600-800 nm, though when combined this dropped to just above 0.2 for the same range. PLS and SMLR analysis of both varieties resulted in many wavelength selections within the same range as high correlation wavelengths and 1st derivatives separately and combined selected several wavelengths to have a high significance between 360-500 nm. These results indicate that the physical changes associated with internal bruising that occur have the highest effect on reflectance in this range. Melanin was known to effect wavelengths around 475 nm, which indicates that the two varieties have different physical changes that affect the results, while combining the varieties targets wavelengths around melanin as the most significant.

For shatter damage, both varieties show significant correlation coefficient above 0.4 between 360-660 nm with only ‘Fabula’ dipping below this between 440-490 nm while a combination of the two varieties maintained significant correlation through the entire same range. PLS and SMLR analysis determined that the most significant wavelengths were between 360-600 nm for both varieties and the combined data, as well as a few values in the up 700 nm range using 1st derivative. The results of analysis show where both varieties have similar reflectance due to the presence of potato tuber starches present in the flesh.

For greening damage, ‘Fabula’ had significant correlation coefficient above 0.4 for the entire range, while ‘Red La Soda’ showed significant correlation between 510-570 nm and 590-700 nm above 0.4. Combining the two varieties resulted in a correlation coefficient range above 0.4 between 376-505 nm and 580-715 nm. PLS and SMLR analysis determined that ‘Fabula’ had the most significant wavelengths between 760-800 nm, 702 nm, 503 nm and between 360-385 nm. Using 1st derivatives, wavelengths between 440-770 nm were found to be significant. ‘Red La Soda’ had most significant wavelengths between 618-698 nm and 1st derivatives in the range on 400-800 nm. Combining the data resulted in most significant wavelengths being between 670-683 nm and at 517 nm. The 1st derivative data determined wavelengths between 700-800 nm and 360-580 nm to be highly significant. Many of the wavelengths determined to be significant were within the photosynthetically active region of 450 nm to 670 nm, which had the most significant influence in the visible light range; solanin would have had an effect on significant reflectance changes outside this range.

For sunscald damage, ‘Fabula’ showed significant correlation above 0.4 between 368 and 800 nm, while ‘Red La Soda’ showed significant correlation between 360- 514 nm and 611- 800 nm. Combining of both varieties resulted in a slightly reduced range of significant wavelengths between 360-477 nm and 618-800 nm. PLS and SMLR analysis determined the most significant wavelengths for ‘Fabula’ to be between 777-800 nm and 360-440 nm, while 1st derivative wavelengths were between 600-800 nm for PLS and 500-800 nm for SMLR. ‘Red La Soda’ was found to have most significant wavelengths between 640-800 nm and 360-366 nm for PLS and 433 nm and 435 nm for SMLR, while 1st derivative had values in the range between 420-725 nm. Combining the data resulted in the most significant wavelengths being between 720-800 nm and 580-630 nm with SMLR. The 1st derivative data determined significant wavelengths to be

between 680-800 nm with PLS and between 430-555 nm with SMLR. The reflectance changes in sunscalded samples would be caused by the radiative burning caused by high temperatures and sun exposure, which caused chemical changes in the tuber surface and subsurface areas.

For brown rot 'Fabula', 'Red La Soda' and combining the two varieties showed a significant correlation coefficient above 0.4 for the entire range. PLS and SMLR analysis determined the most significant wavelengths for 'Fabula' to be between 360-380 nm using PLS and 680-690 nm with SMLR. Using 1st derivative data wavelengths between 420-800 nm were found with both methods. 'Red La Soda' had its most significant wavelengths selected between780-800 nm and 360-390 nm. 1st derivative analysis selected wavelengths between 500-800 nm. Combining the two sets of data resulted in wavelength selection between 700-800 nm and 360-400 nm, while the 1st derivative data selecting most significant wavelengths between 400-800 nm. Brown rot caused by the bacterium *Ralstonia solanacearum* had an effect on reflectance at both ends of the measured range associated with the rotting of tuber flesh which causes brown-grey discoloration and the development of creamy pus.

For growth cracking, 'Fabula' had a reflectance between 360-800 nm with significant correlation above 0.4, while 'Red La Soda' and a combination of both varieties showing significance between 360-495 nm and 590-800 nm. PLS and SMLR analysis determined the most significant wavelengths for 'Fabula' to be between 360-400 nm and 785-800 nm using PLS opposed to SMLR which determined the range between 470-550 nm to be most significant. The 1st derivative wavelengths were found to be between 450-800 nm with both methods. 'Red La Soda' had its most significant wavelengths between 400-800 nm, while the 1st derivative of data determined the wavelengths to be between 430-640 nm. Combining the data resulted in most significant wavelengths being between 660-800 nm and 375-400 nm. The 1st derivative data

selected wavelengths from the entire spectrum measured for both methods. All reflectance changes were affected by the suberization of tuber flesh in order to repair damage. Reflectance changes would have also been influenced by the development of H_2O_2 accumulation, which causes suberization to occur.

For insect damage, 'Red La Soda' between 360-510 nm and 580-800 nm was significantly above 0.4. PLS analysis determined the most significant wavelengths for 'Red La Soda' were between 750-800 nm and 360-530 nm. While 1st derivative wavelengths were between 420-800 nm. Insect damage repair was performed by the same suberization process as growth cracking and resulted in similar wavelength ranges being most significant on reflectance changes.

Each set of data for 'Fabula' and 'Red La Soda' had ranges of spectral wavelength with a correlation coefficient value |r| greater than 0.4 between 360 nm and 800 nm; this shows that there is a correlation between wavelength values and percent area damaged being scanned which can be used to calibrate a model in order to predict damage. PLS and SMLR analysis showed that all sample disorders had significant wavelengths with a high coefficient of significance between either 360-500 nm or 600-800 nm, if not both. This would mean that spectral wavelength scans could be concentrated on these areas in order to calibrate models for prediction of damage faster on a packaging line. Lu and Arianna (2002) referenced that advances in CCD technology have enabled rapid acquisition of spectral information in the visible and short NIR region (400-1100 nm) which would allow be very advantageous for packaging line applications using the wavelengths found to accurately predict the presence of tuber disorders.

However, as Singh et al. (2005) stated, spectroscopic techniques require a set of well-designed calibration processes in order to achieve the best models to predict specific parameters

of interest in a food product. Thus more data would need to be collected in order to allow for more accurate prediction of specific disorders and whether or not suffered damage would warrant removal from the packaging line due to models having greater error associated with undamaged healthy tubers.

Table 3-1. Number of samples collected for each variety and disorder.

	'Fabula'		'Red La Soda'	
Disorder	Damaged	Healthy	Damaged	Healthy
Bruising	14	29	15	24
Shatter	17	79	17	77
Greening	13	20	13	20
Sunscald	12	79	12	77
Brown rot	13	79	15	77
Growth cracking	14	79	14	77
Insect damage	-	-	5	77

Fabula 3-1. 'Fabula' Internal Bruising

Figure 3-2. 'Red La Soda' Internal Bruising

Figure 3-3. ‘Fabula’ Shatter

Figure 3-4. ‘Red La Soda’ Shatter

Figure 3-5. ‘Fabula’ Greening

Figure 3-6. ‘Red La Soda’ Greening

Figure 3-7. ‘Fabula’ Sunscald

Figure 3-8. ‘Red La Soda’ Sunscald

Figure 3-9. ‘Fabula’ Brown Rot

Figure 3-10. ‘Red La Soda’ Brown Rot

Figure 3-11. ‘Fabula’ Growth Cracking

Figure 3-12. ‘Red La Soda’ Growth Cracking

Figure 3-13. ‘Red La Soda’ Insect Damage

Figure 3-14. Cary 500 Scan Spectrophotometer (Varian, Inc. Palo Alto, CA)

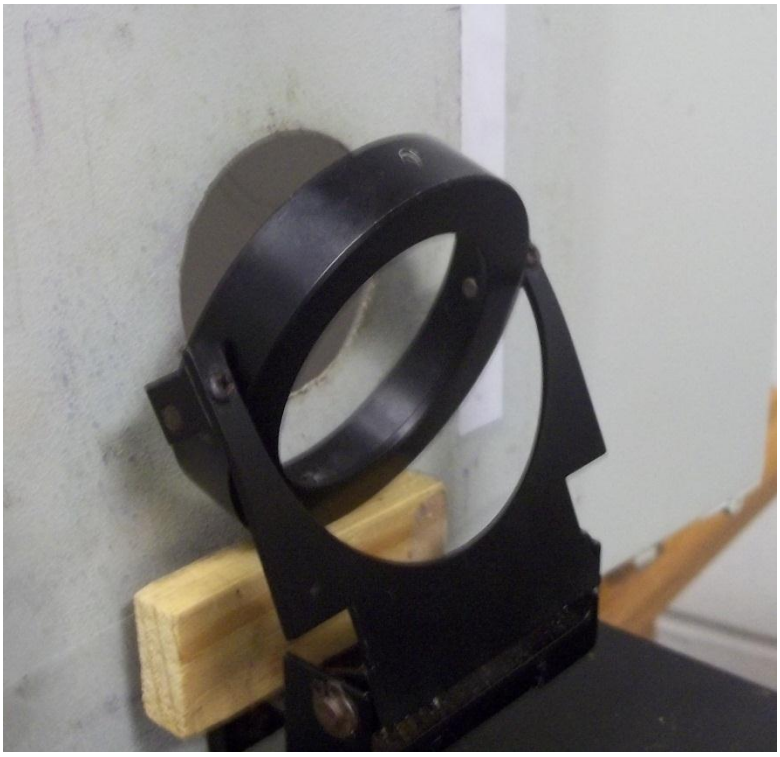

Figure 3-15. Cary 500 Sample measurement port

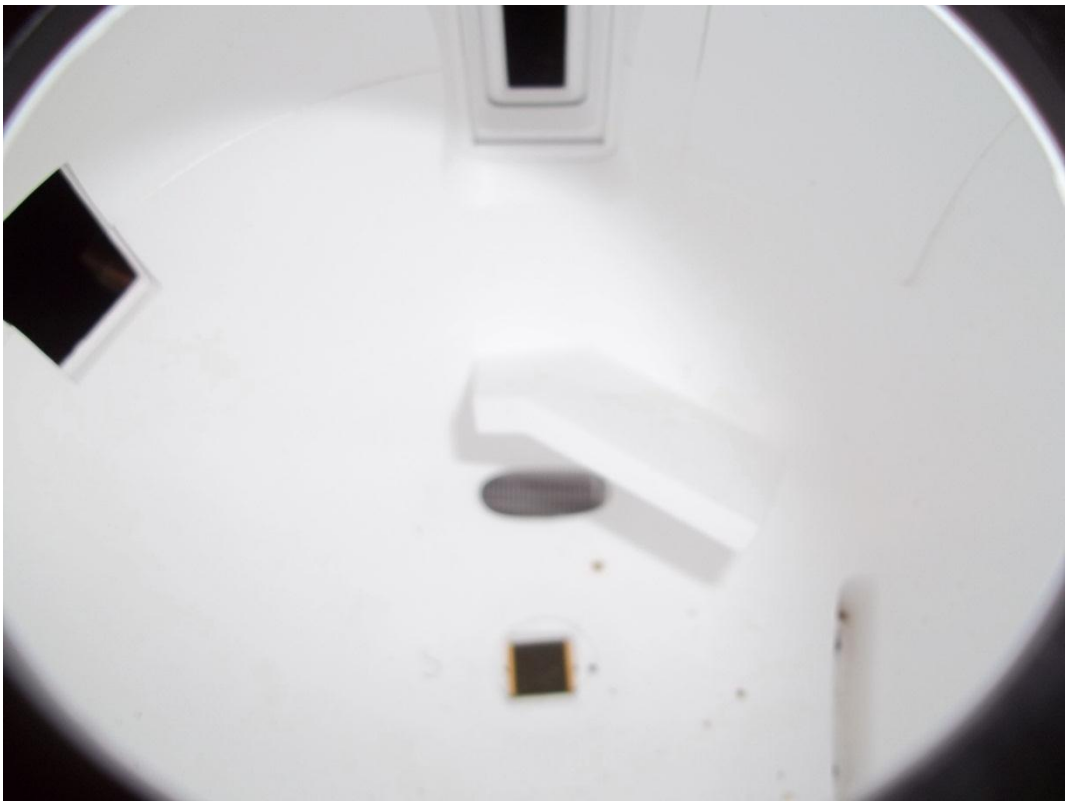

Figure 3-16. Integrating sphere with white polytetrafluoroethylene coating

Figure 3-17. PTFE calibration disk

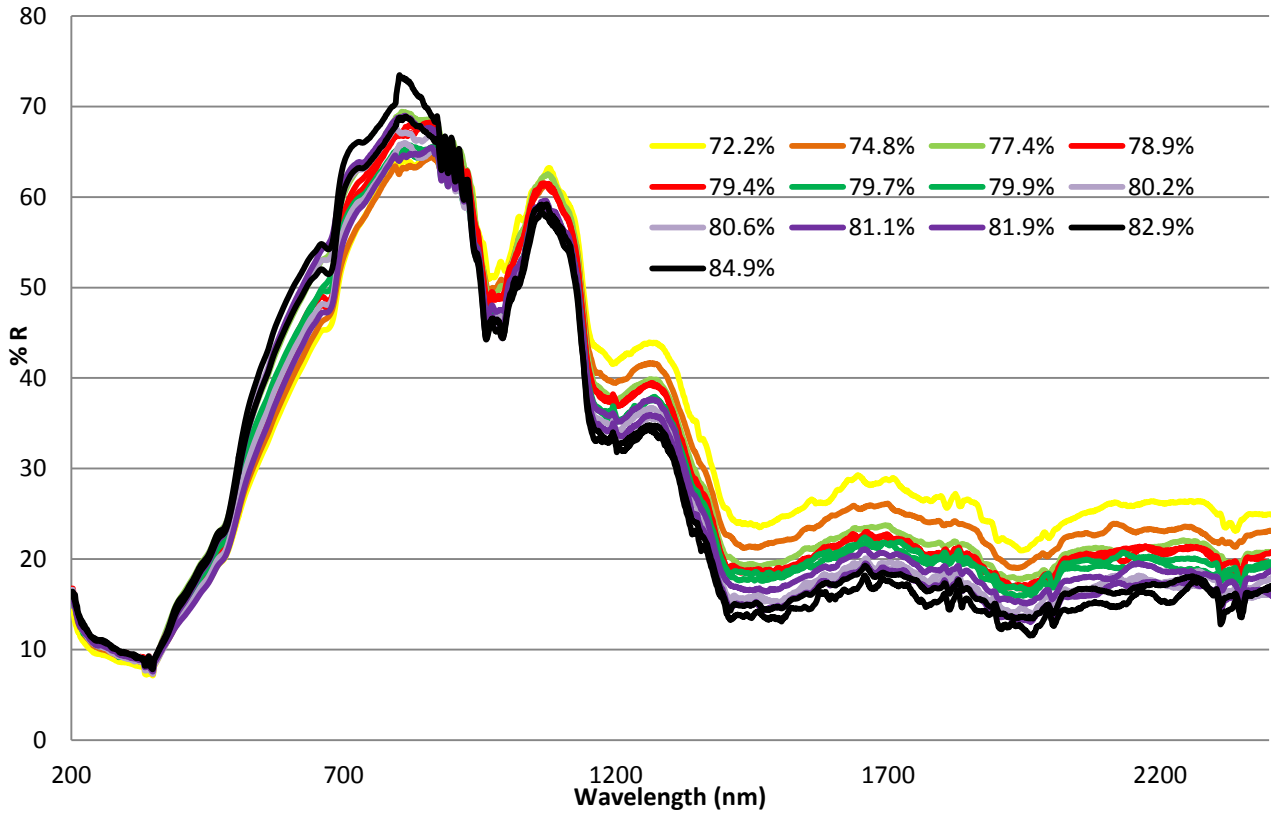

Figure 3-18. 'Fabula' Moisture Content Reflectance spectrum (200 nm to 2500 nm)

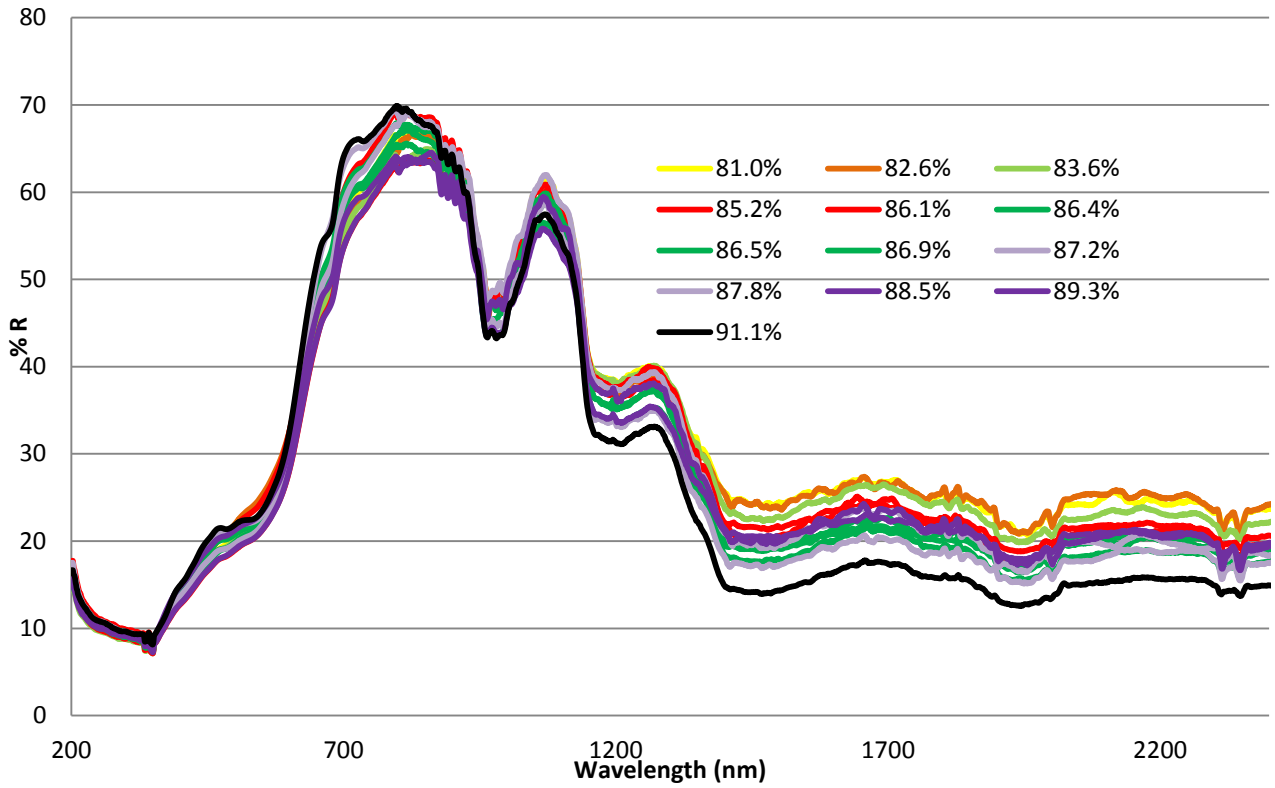

Figure 3-19. 'Red La Soda' Moisture Content Reflectance Spectrum (200 nm to 2500 nm)

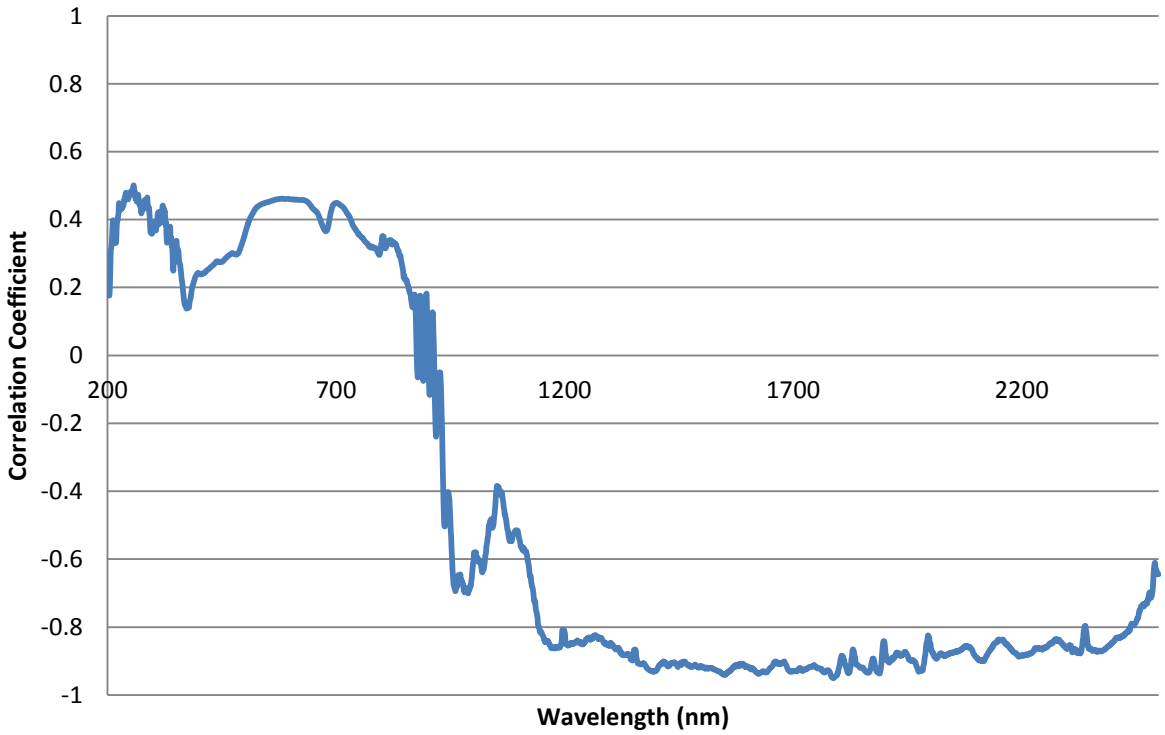

Figure 3-20. 'Fabula' Correlation coefficient between tuber moisture content and wavelength

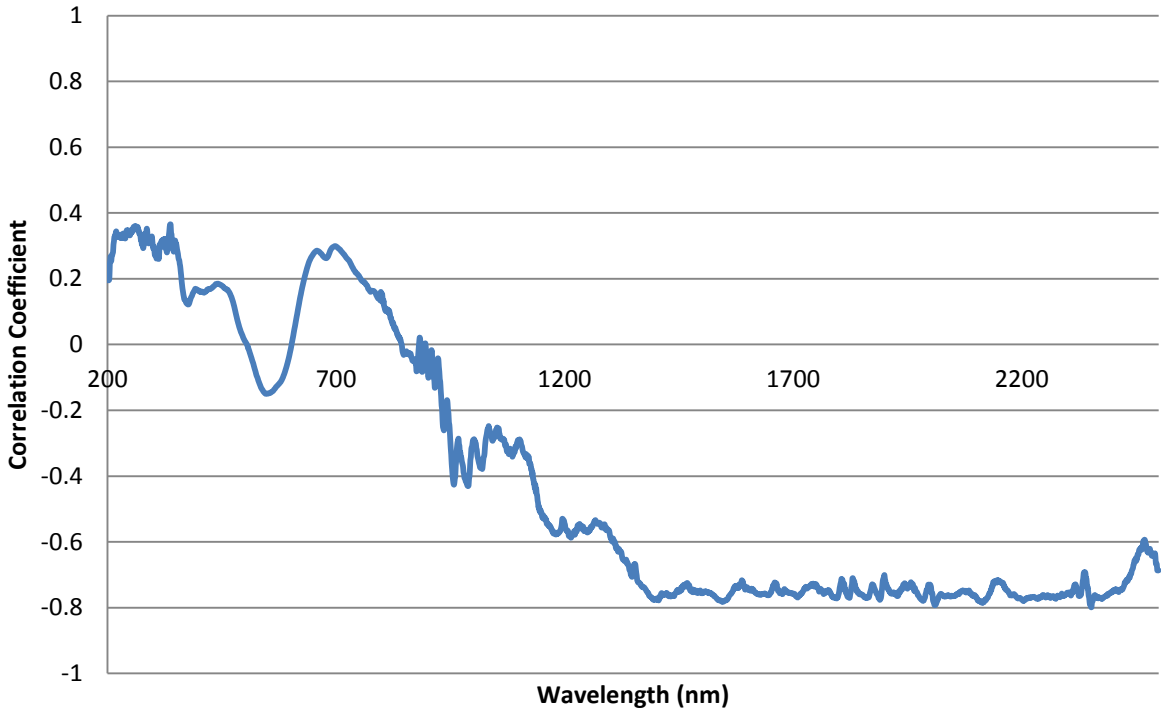

Figure 3-21. 'Red La Soda' Correlation coefficient between tuber moisture content and wavelength

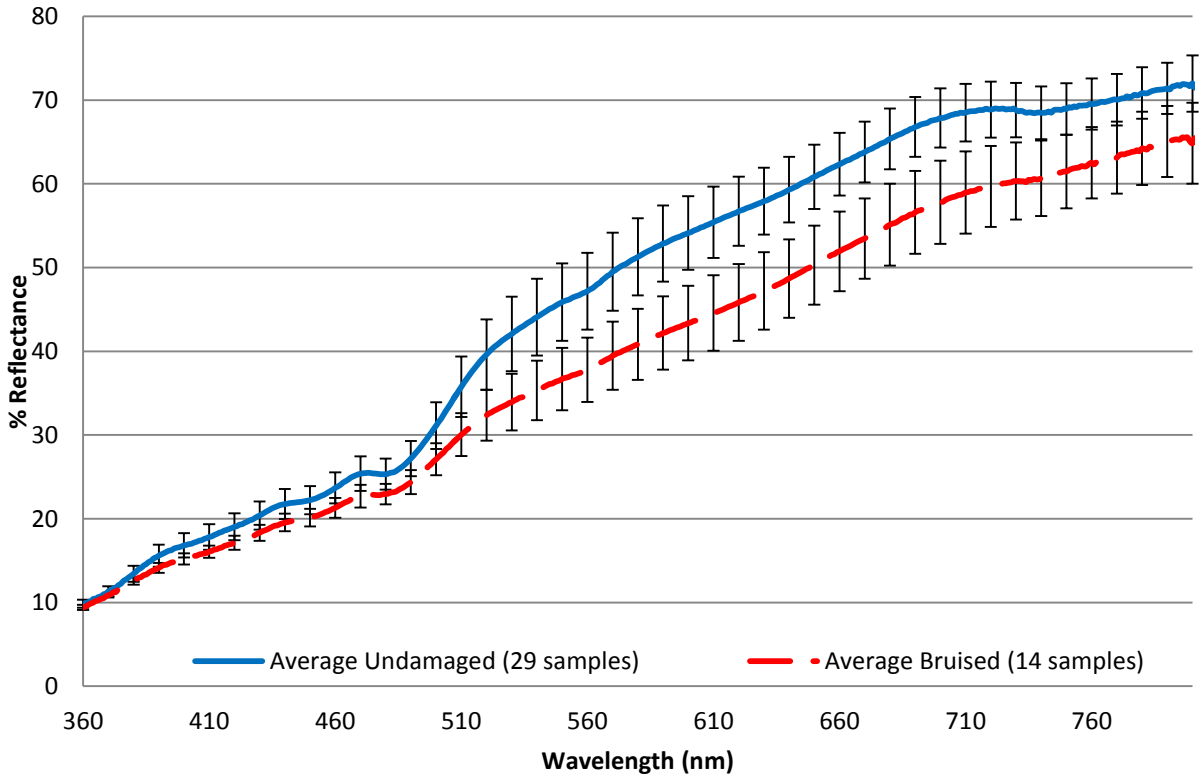

Figure 3-22. 'Fabula' Internal Bruising vs. Undamaged- 6 days storage

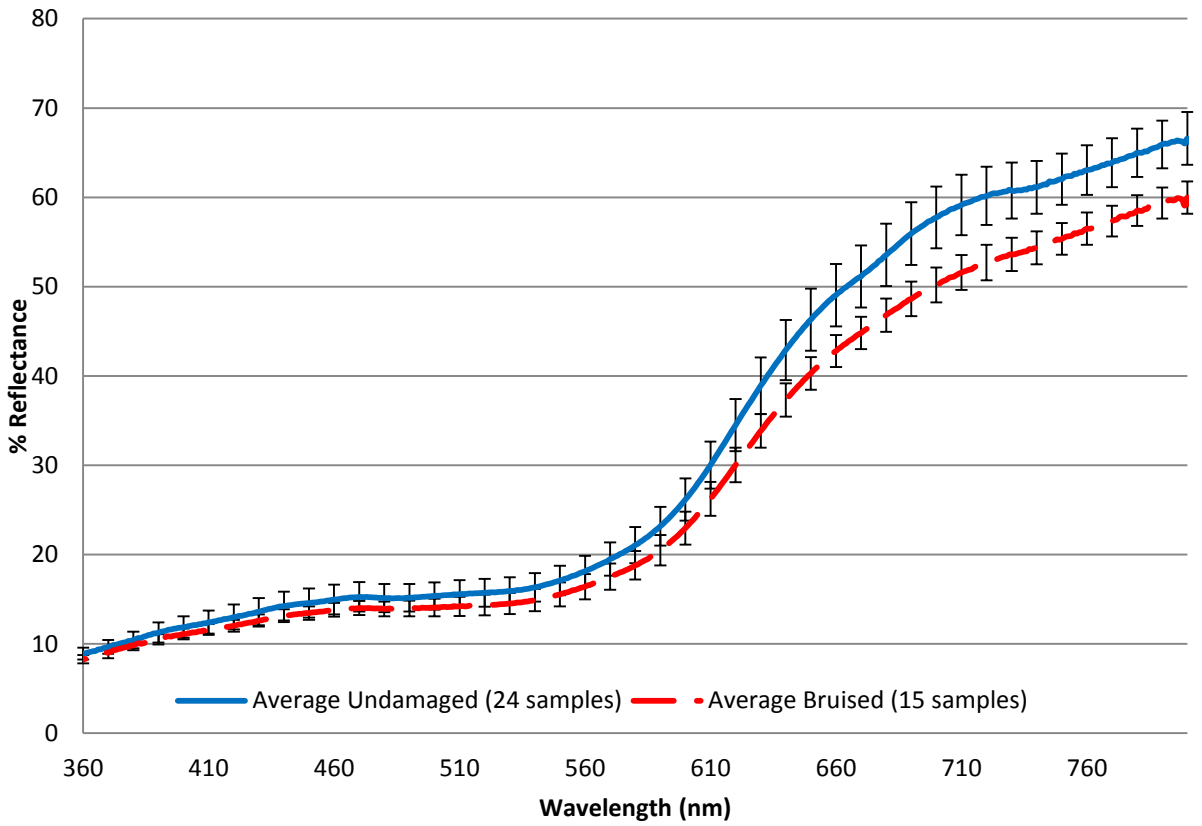

Figure 3-23. 'Red La Soda' Internal Bruising vs. Undamaged- 7 days storage

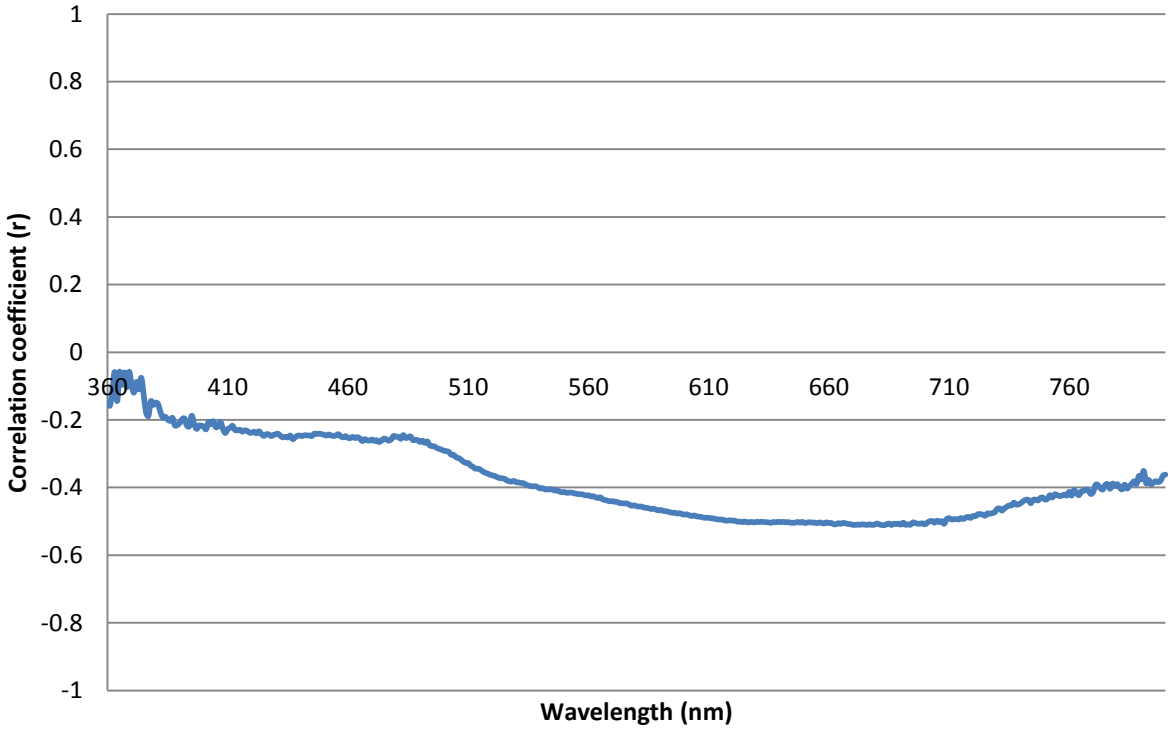

Figure 3-24. 'Fabula' Internal Bruising Correlation coefficients between reflectance at each wavelength and internally damaged tissue concentration.

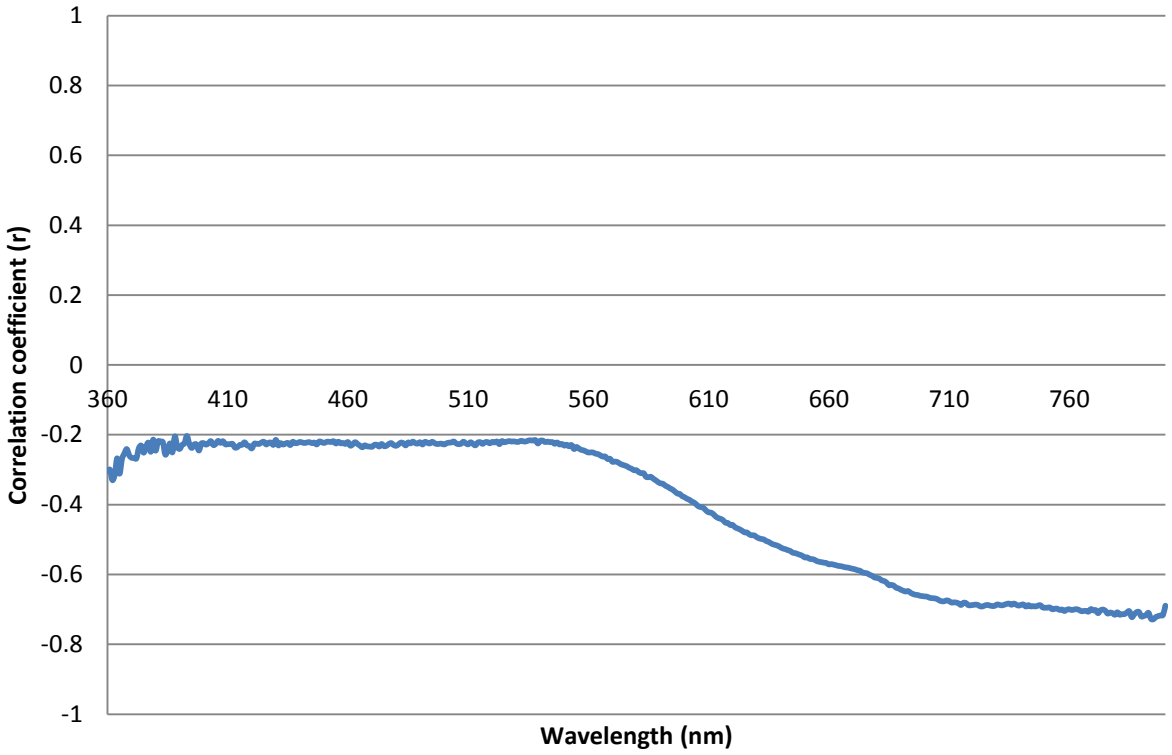

Figure 3-25. 'Red La Soda' Internal Bruising Correlation coefficients between reflectance at each wavelength and internally damaged tissue concentration.

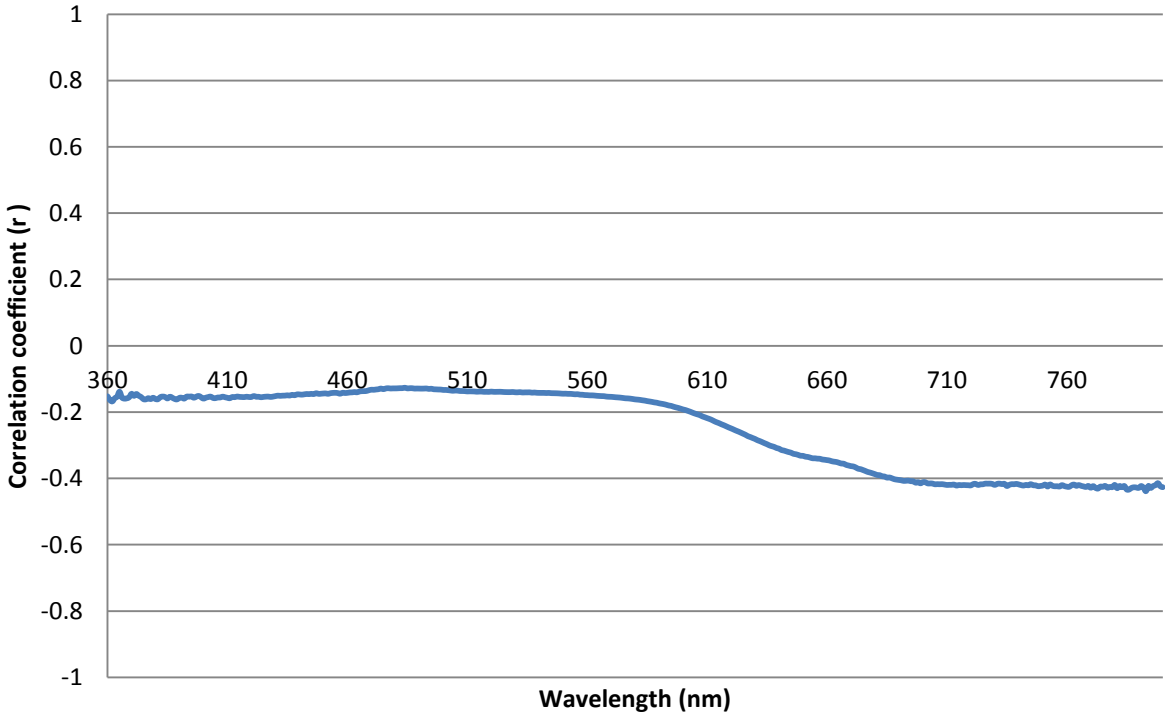

Figure 3-26. Combined Internal Bruising Correlation coefficients between reflectance at each wavelength and internally damaged tissue concentration.

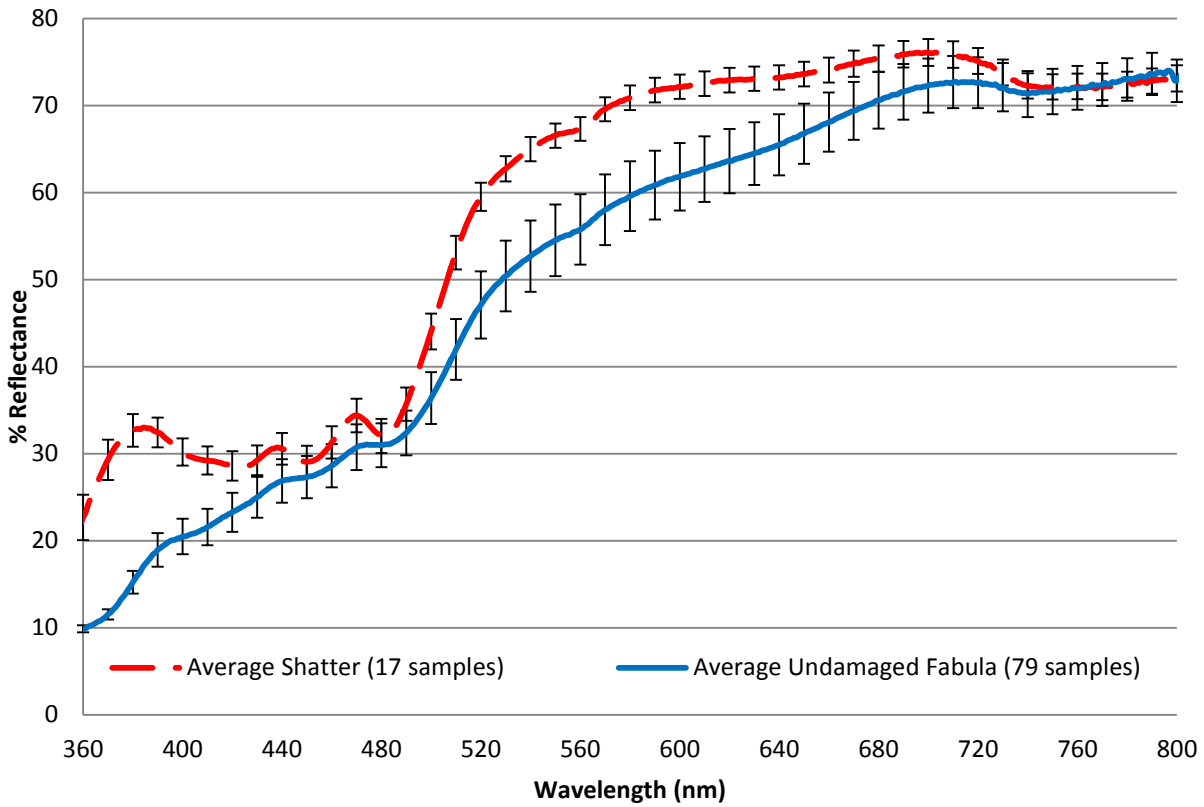

Figure 3-27. 'Fabula' Shatter vs. Undamaged- Day of Harvest

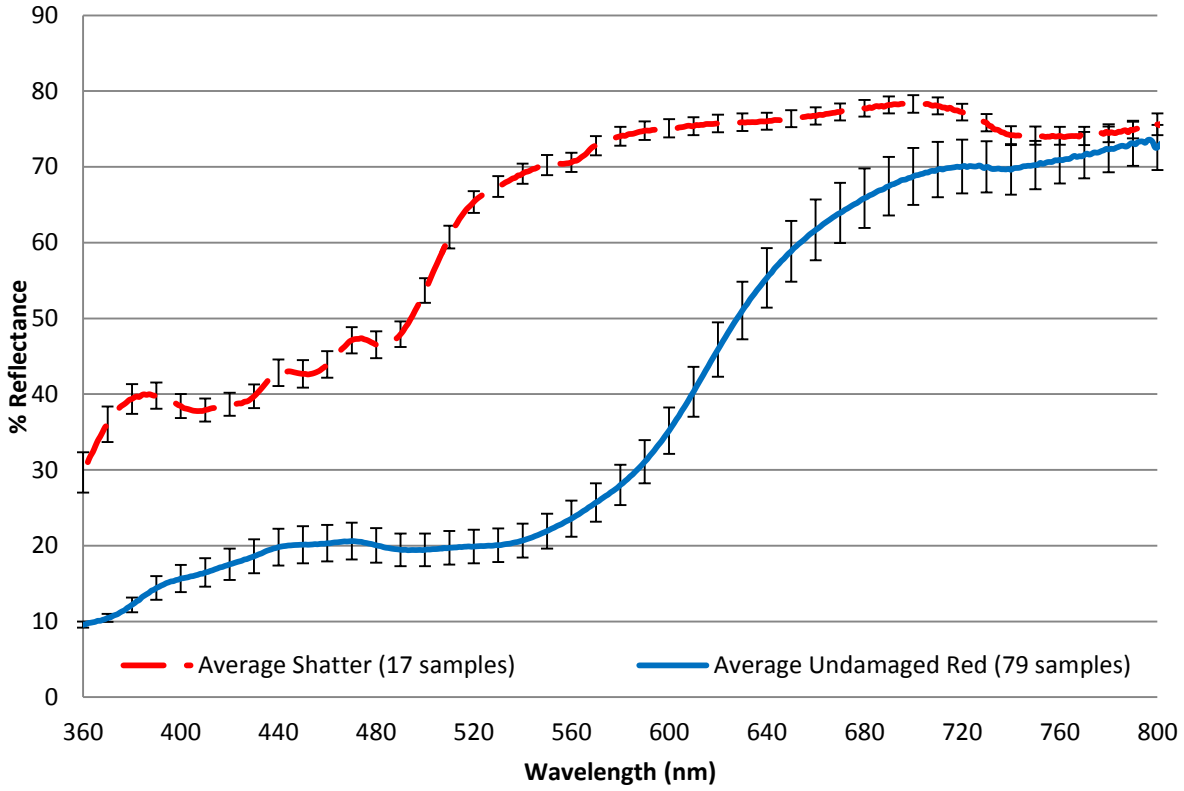

Figure 3-28. 'Red La Soda' Shatter vs. Undamaged- Day of Harvest

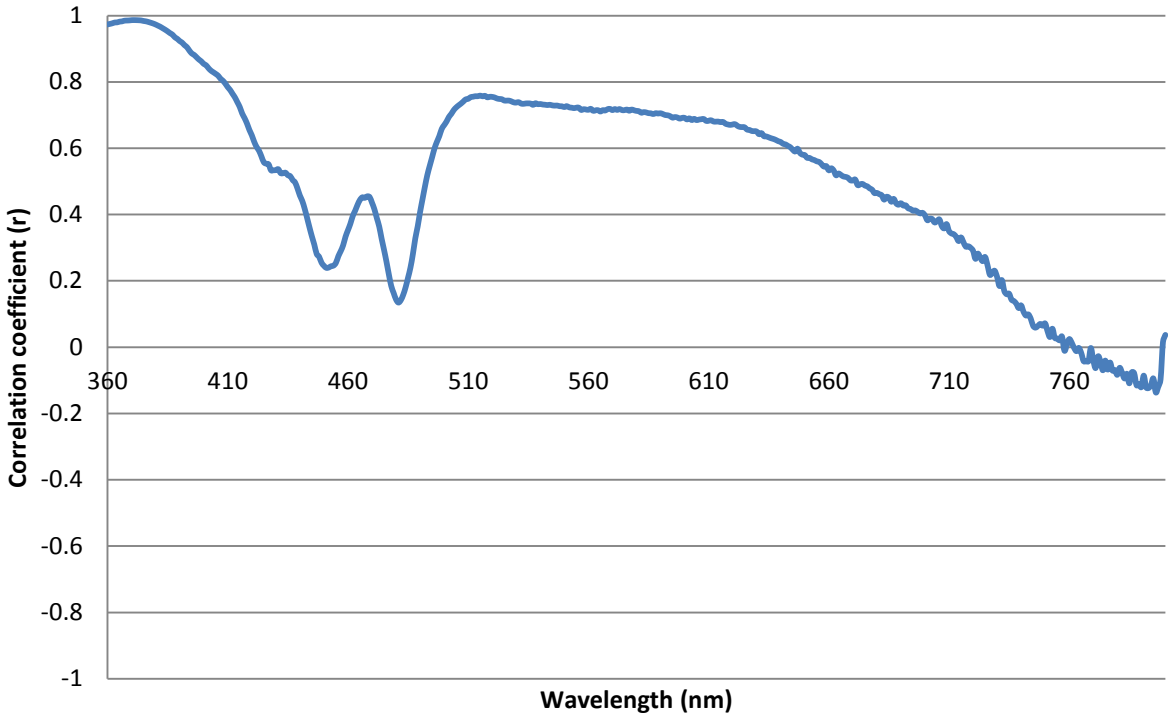

Figure 3-29. 'Fabula' Shatter Correlation coefficients between reflectance at each wavelength and Shatter concentration.

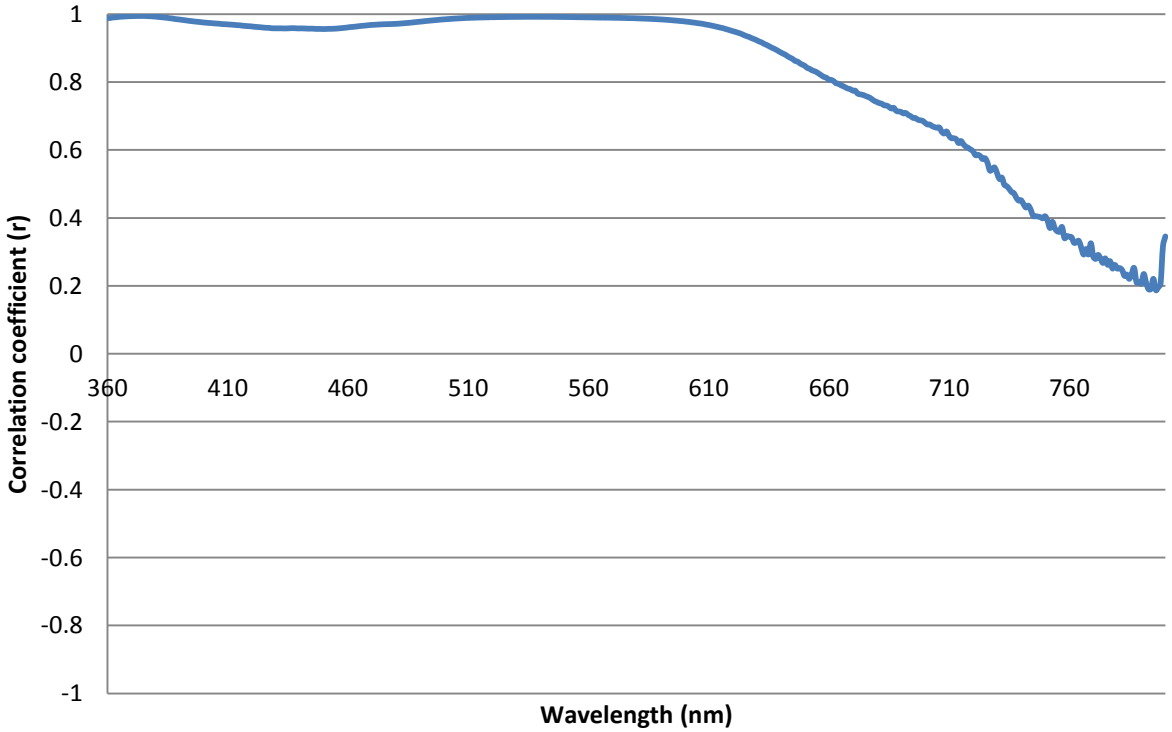

Figure 3-30. 'Red La Soda' Shatter Correlation coefficients between reflectance at each wavelength and Shatter concentration.

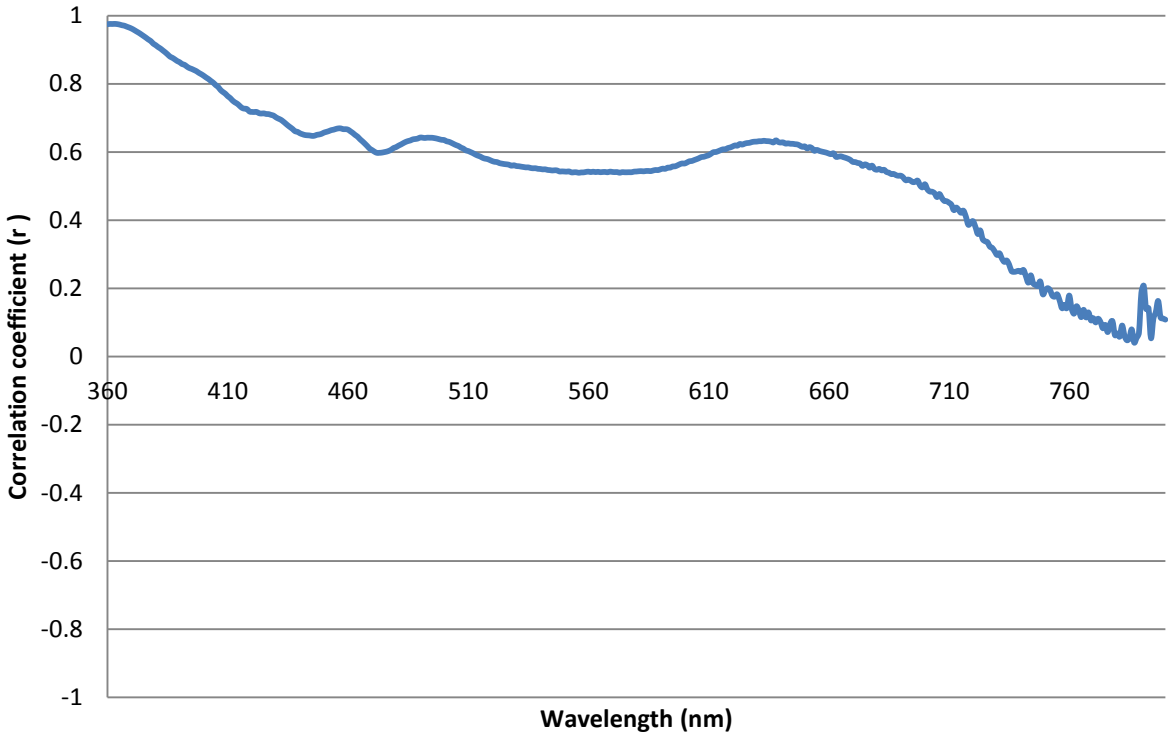

Figure 3-31. Combined Shatter Correlation coefficients between reflectance at each wavelength and Shatter concentration.

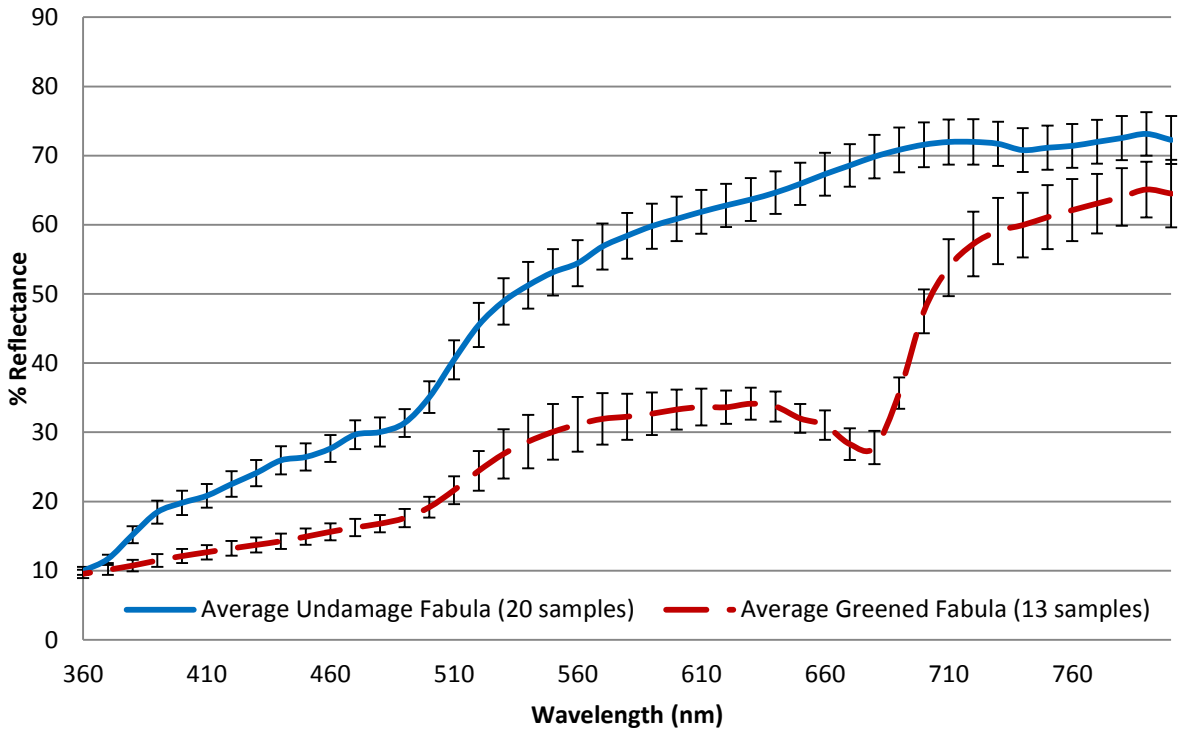

Figure 3-32. 'Fabula' Greening vs. Undamaged- Day of Harvest

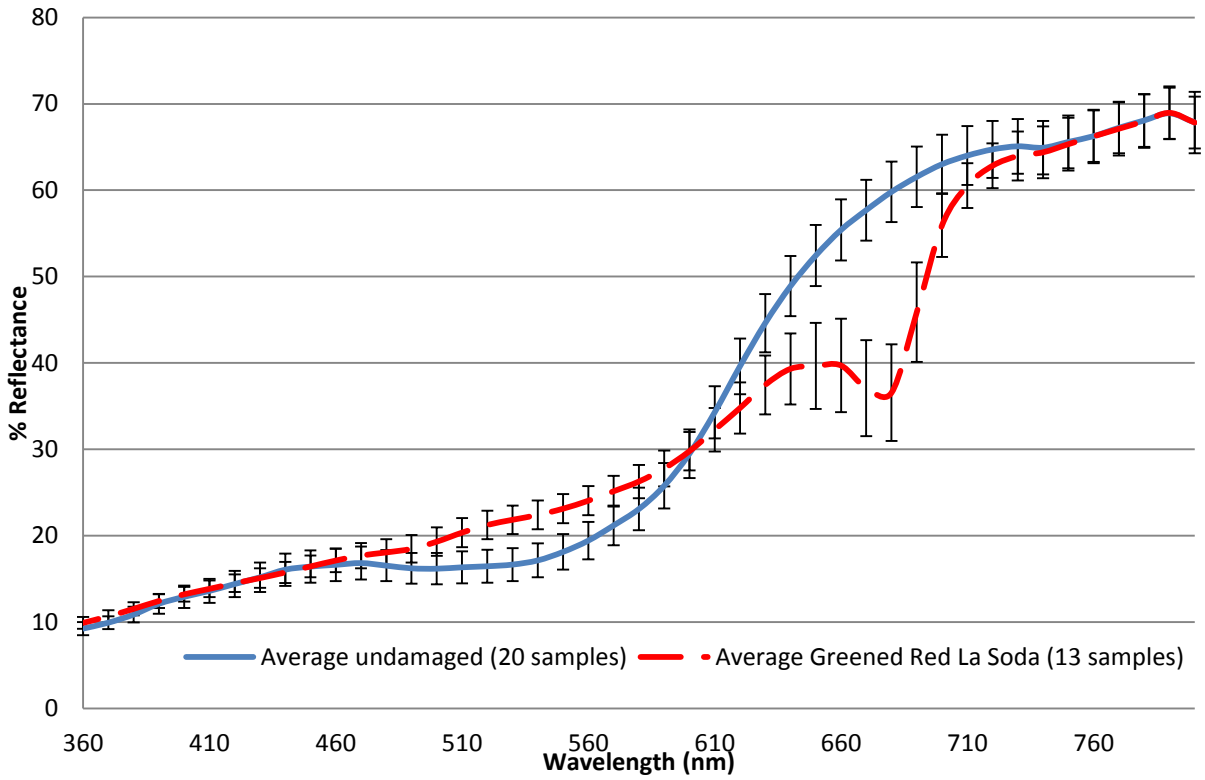

Figure 3-33. 'Red La Soda' Greening vs. Undamaged- Day of Harvest

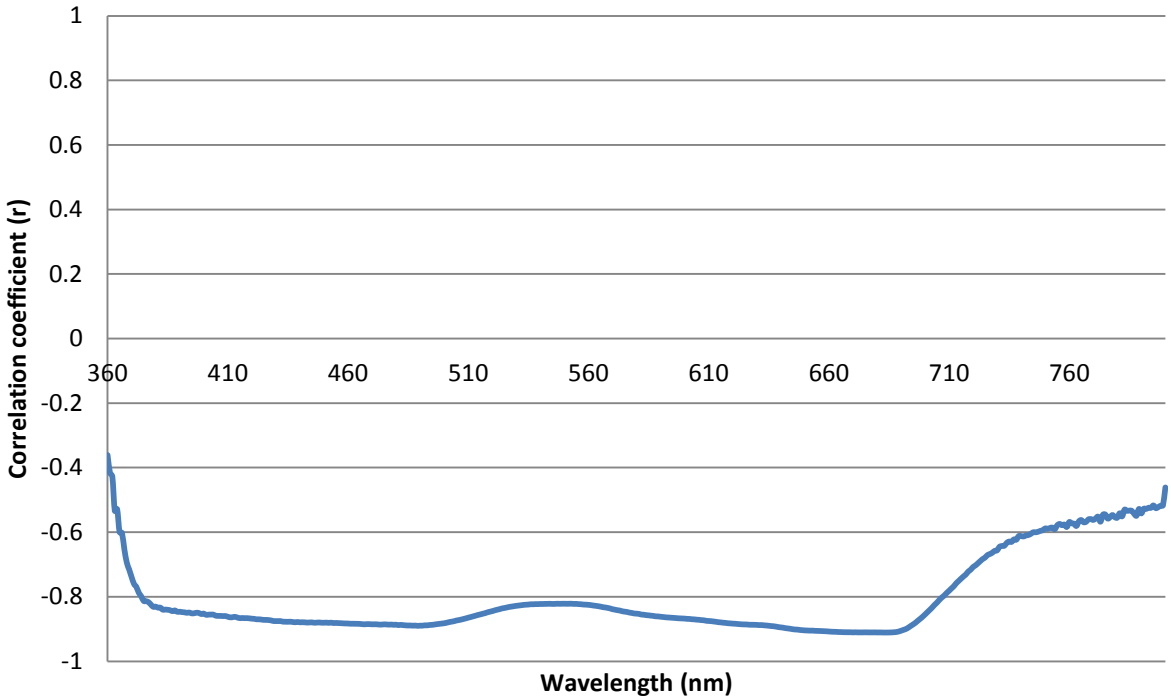

Figure 3-34. 'Fabula' Greening Correlation coefficients between reflectance at each wavelength and Greening concentration.

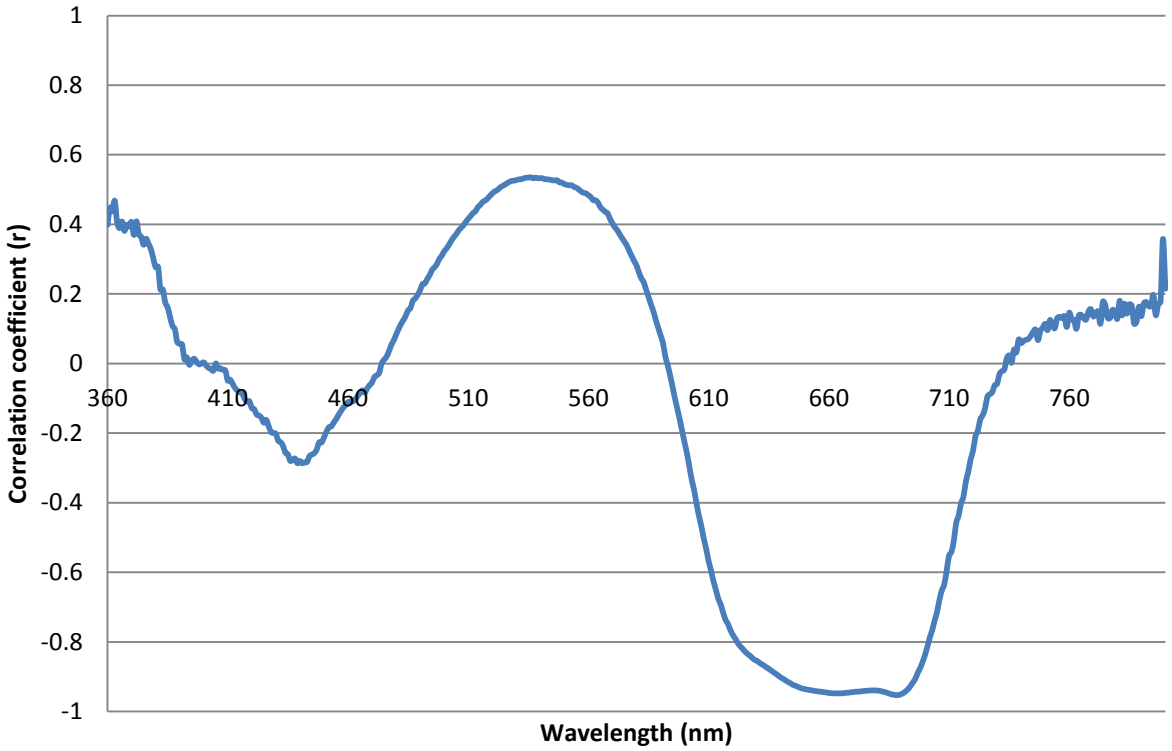

Figure 3-35. 'Red La Soda' Greening Correlation coefficients between reflectance at each wavelength and Greening concentration.

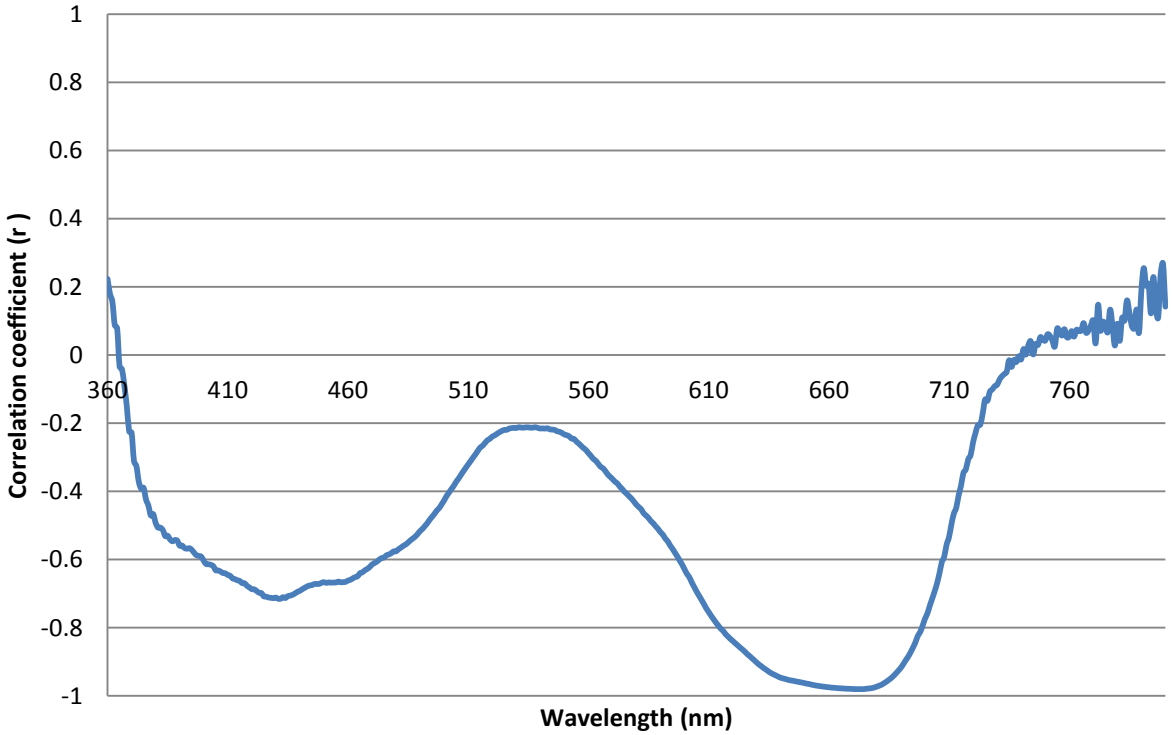

Figure 3-36. Combined Greening Correlation coefficients between reflectance at each wavelength and Greening concentration.

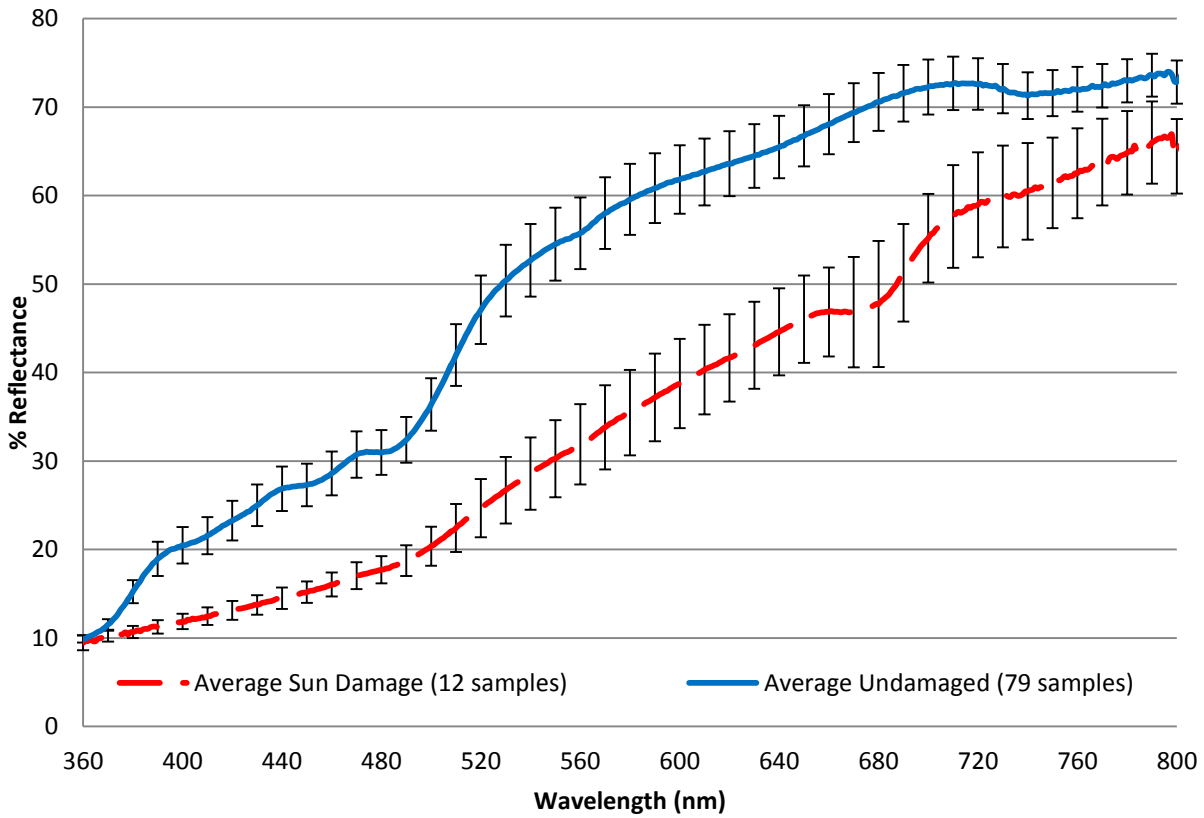

Figure 3-37. 'Fabula' Sunscald vs. Undamaged- Day of Harvest

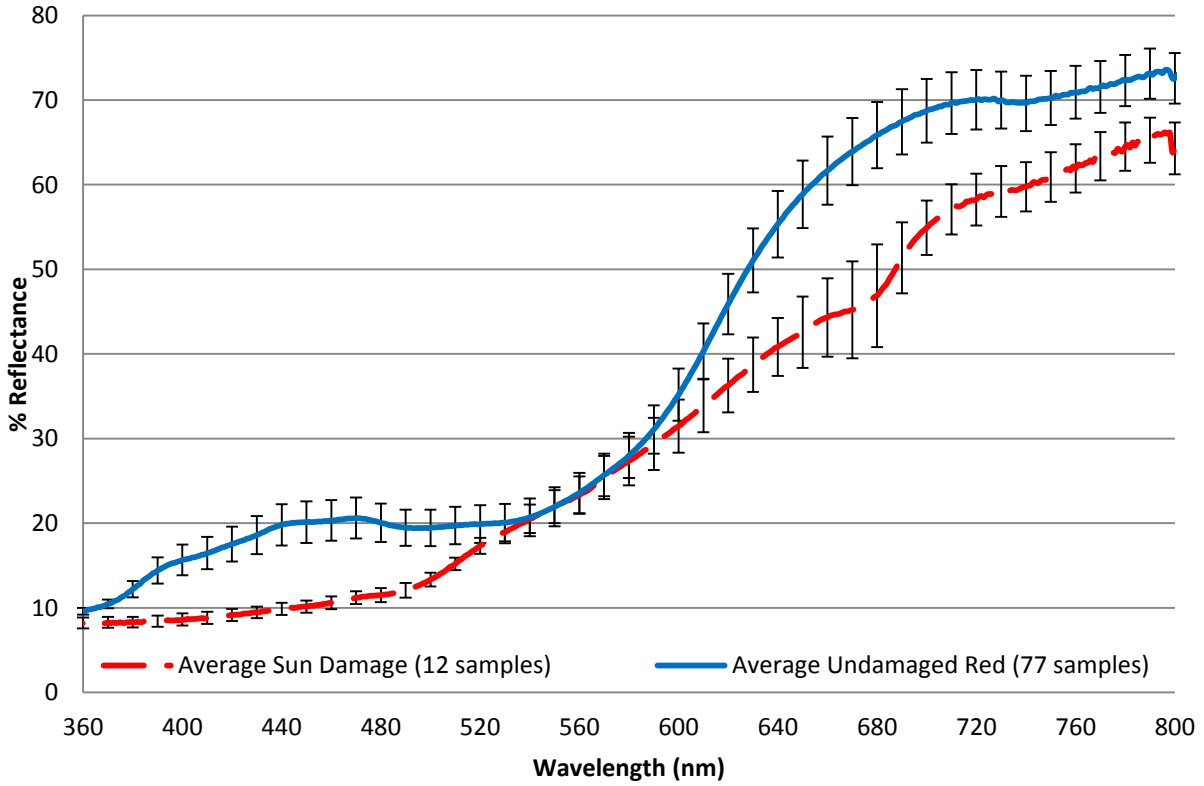

Figure 3-38. 'Red La Soda' Sunscald vs. Undamaged- Day of Harvest

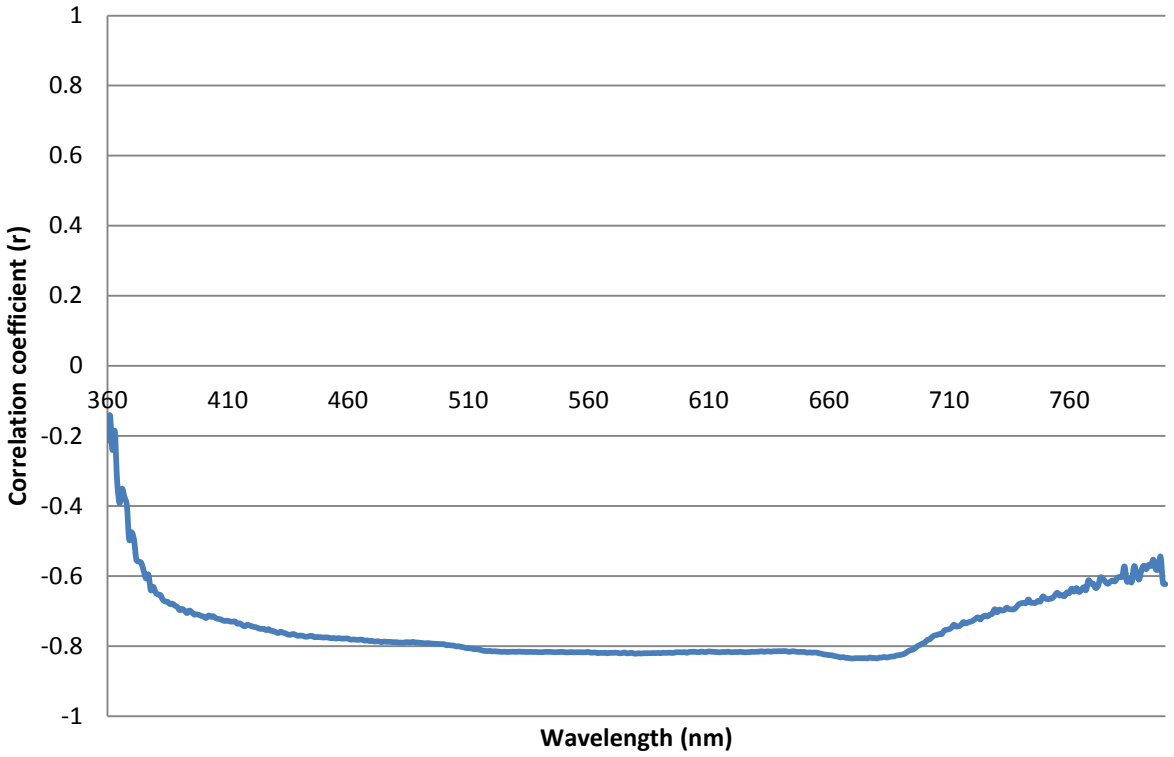

Figure 3-39. 'Fabula' Sunscald Correlation coefficients between reflectance at each wavelength and Sun Damage concentration.

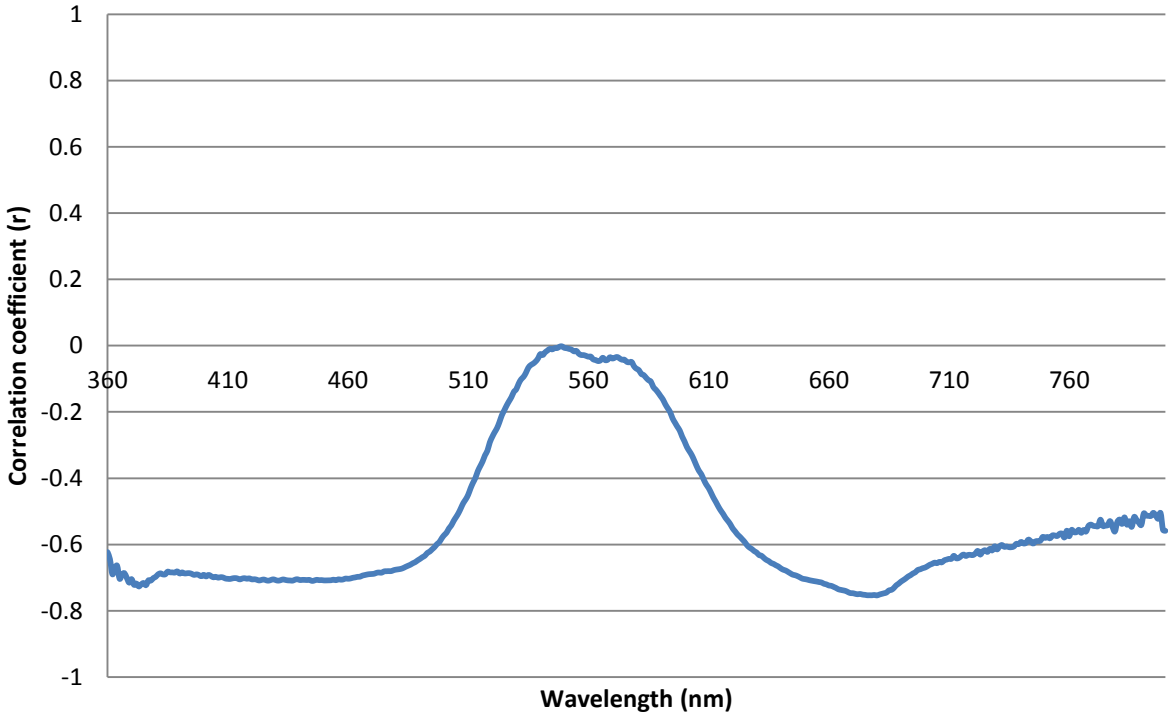

Figure 3-40. 'Red La Soda' Sunscald Correlation coefficients between reflectance at each wavelength and Sun Damage concentration.

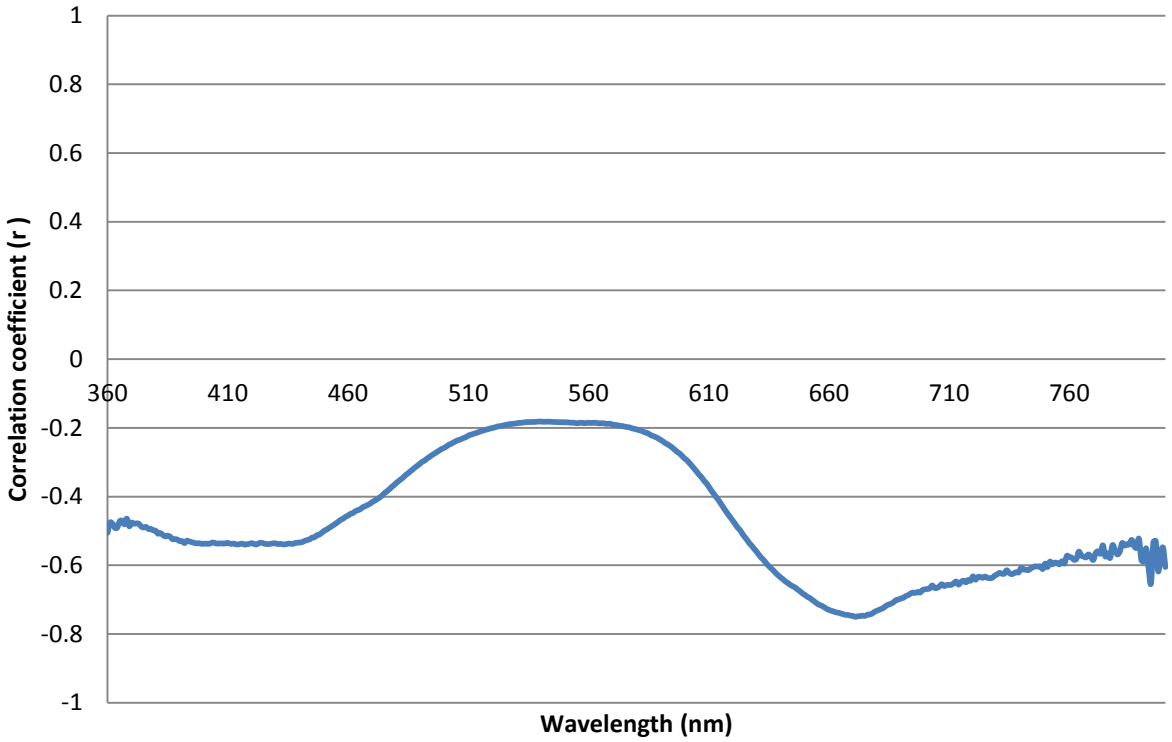

Figure 3-41. Combined Sunscald Correlation coefficients between reflectance at each wavelength and Sun Damage concentration.

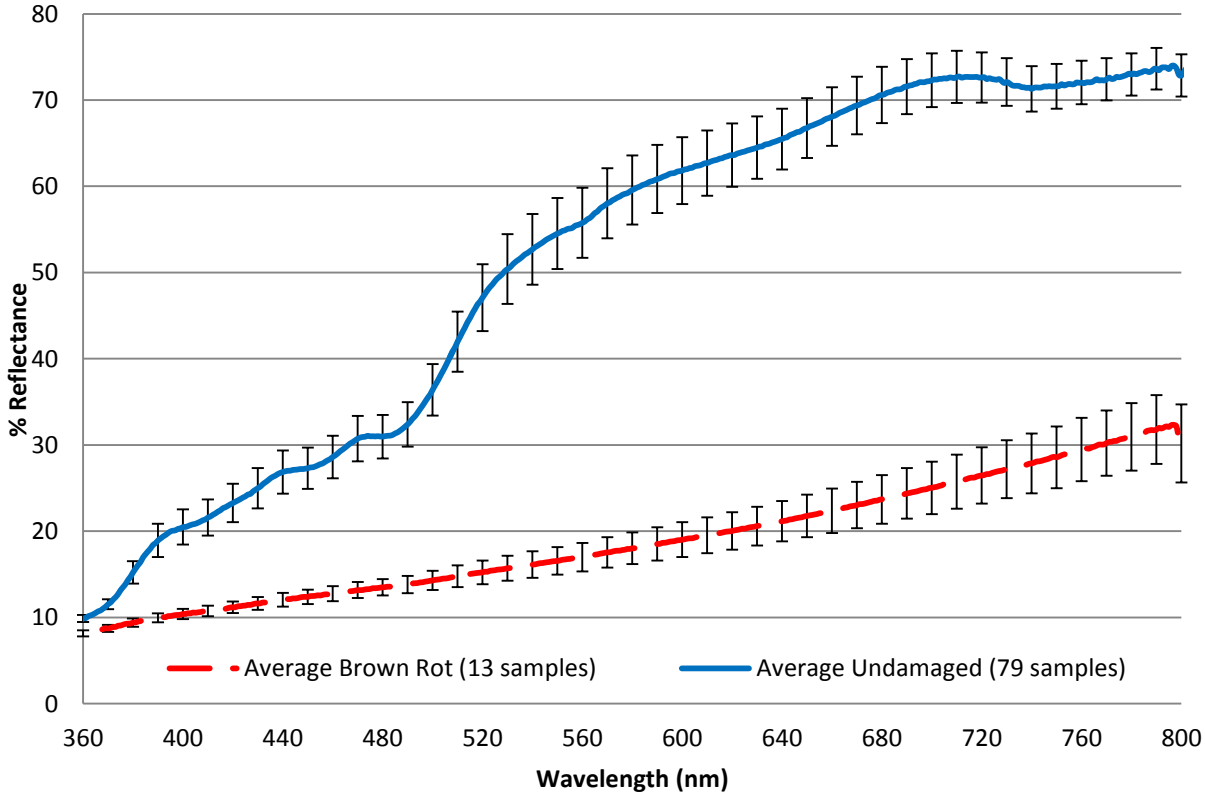

Figure 3-42. 'Fabula' Brown rot vs. Undamaged- Day of Harvest

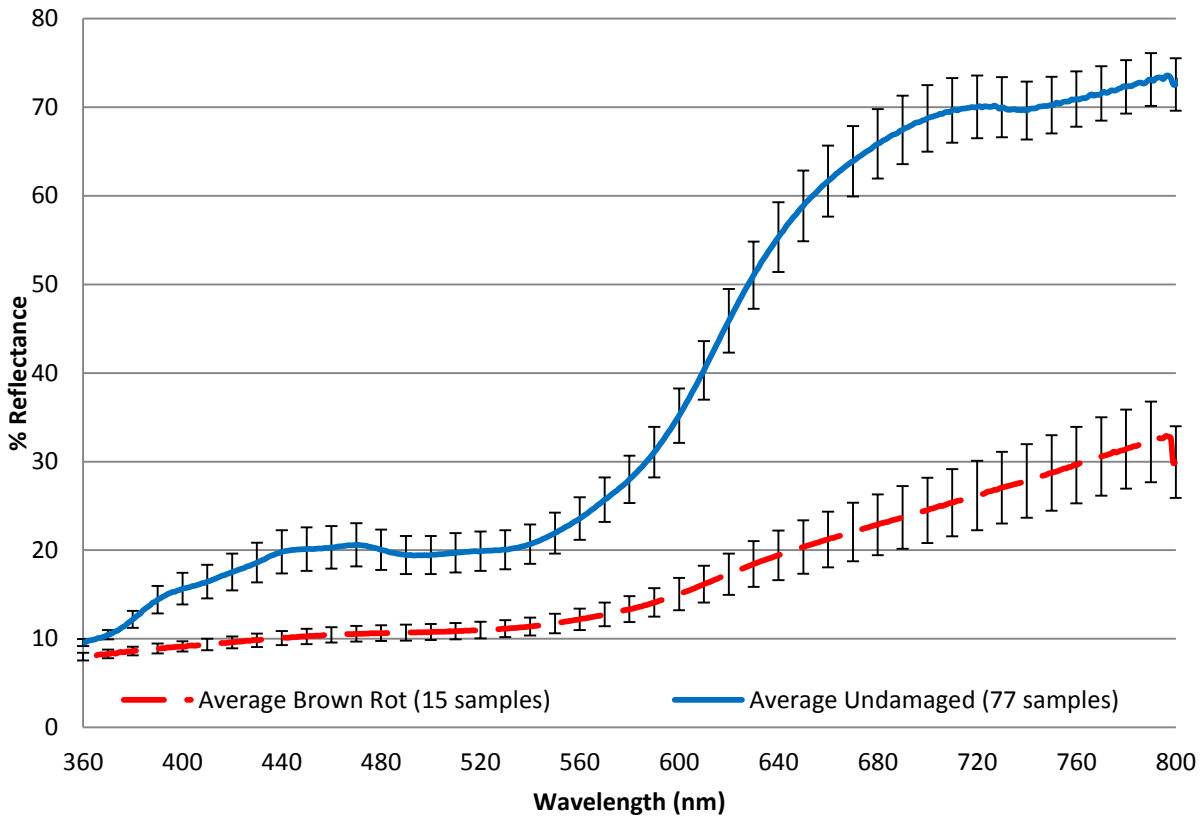

Figure 3-43. 'Red La Soda' Brown rot vs. Undamaged- Day of Harvest

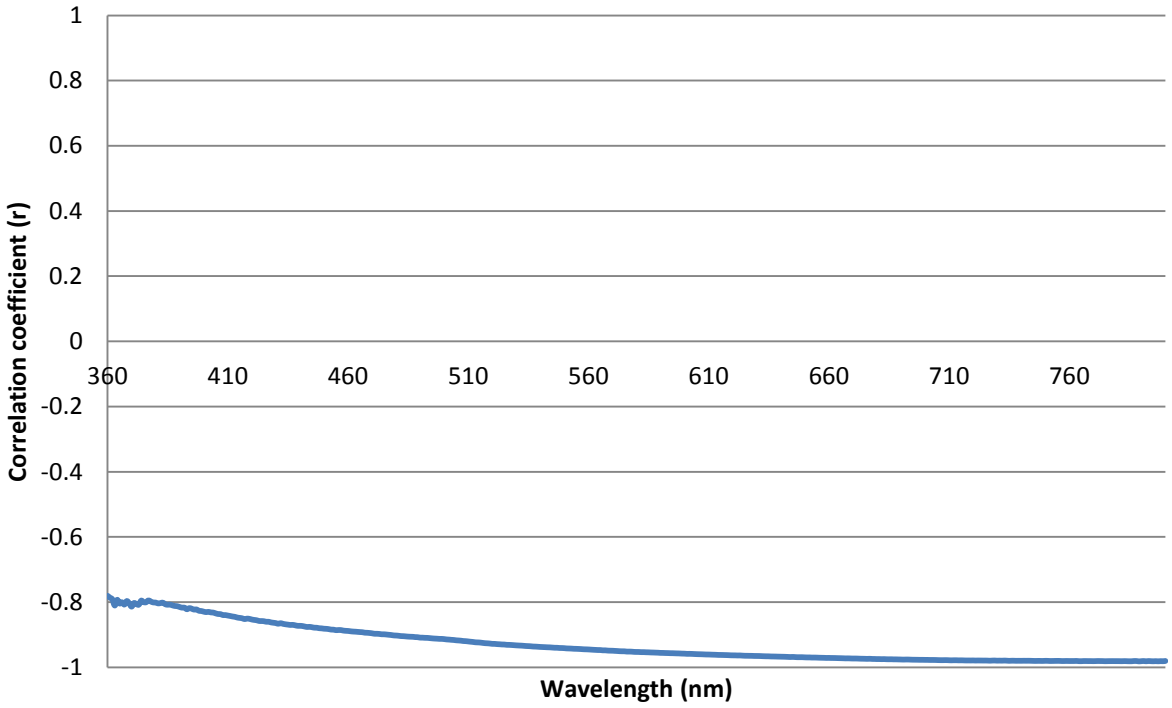

Figure 3-44. 'Fabula' Brown Rot Correlation coefficients between reflectance at each wavelength and Brown rot concentration.

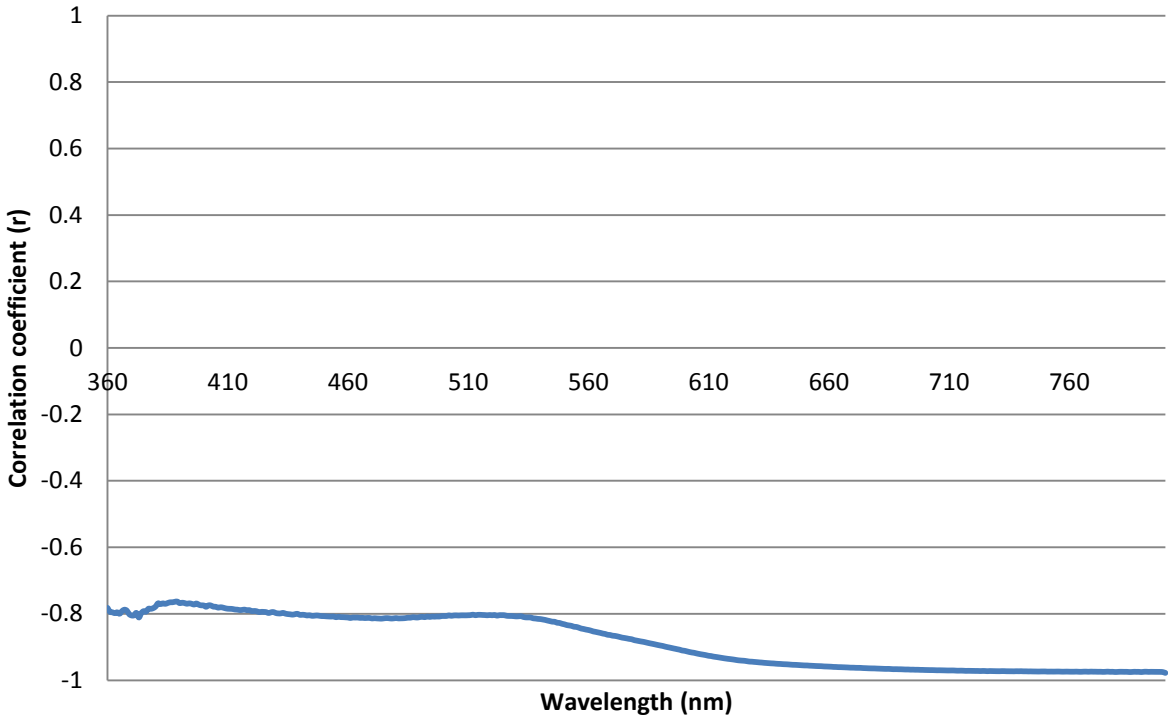

Figure 3-45. 'Red La Soda' Brown Rot Correlation coefficients between reflectance at each wavelength and Brown rot concentration.

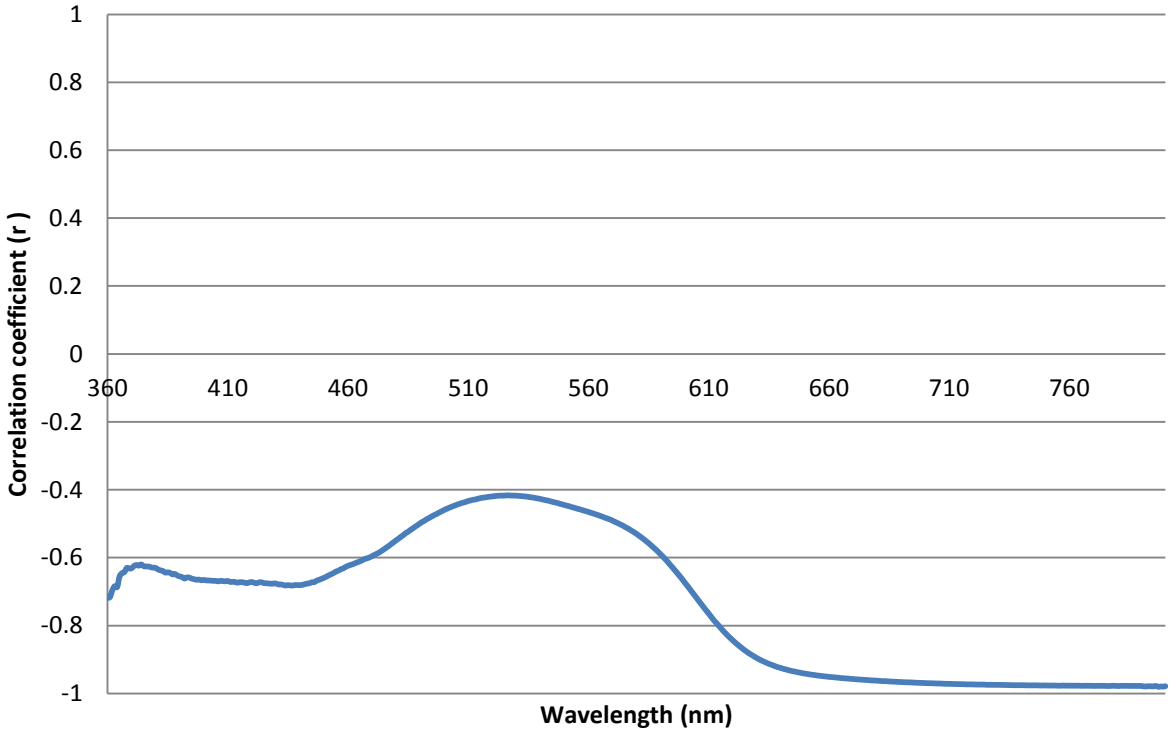

Figure 3-46. Combined Brown Rot Correlation coefficients between reflectance at each wavelength and Brown rot concentration.

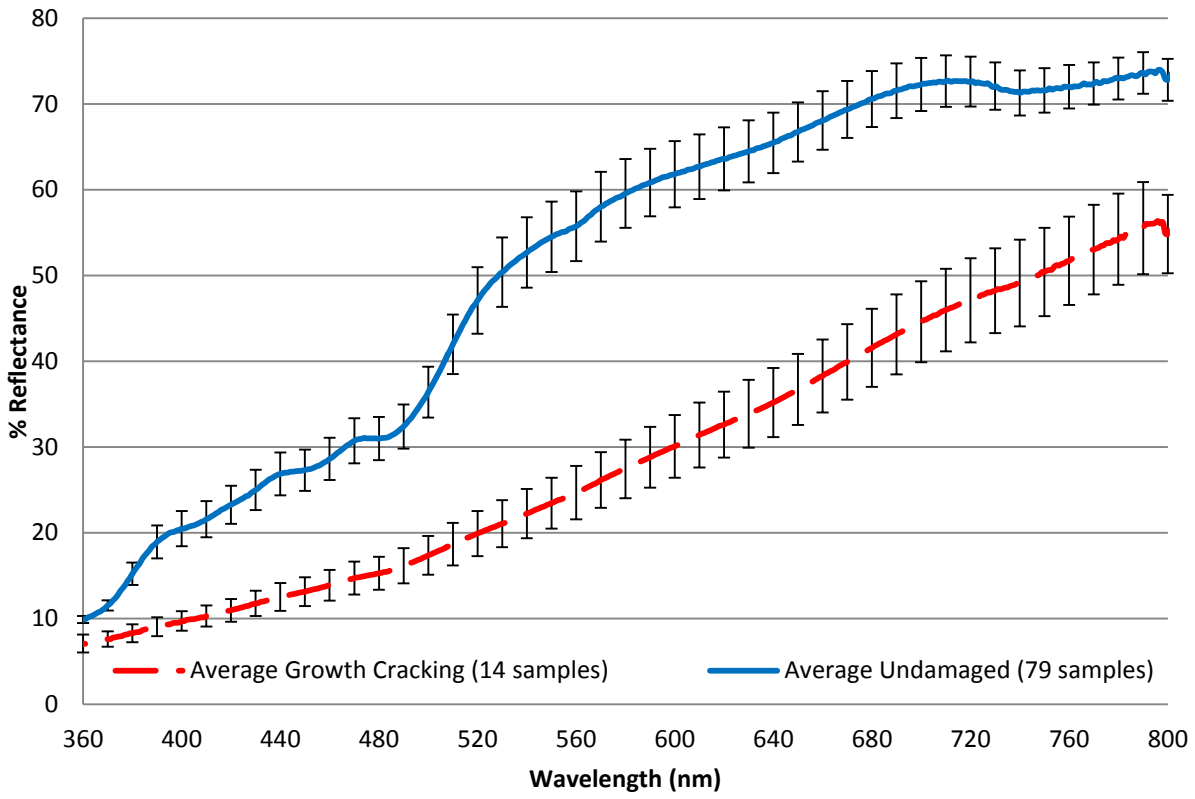

Figure 3-47. 'Fabula' Growth Cracking vs. Undamaged- Day of Harvest

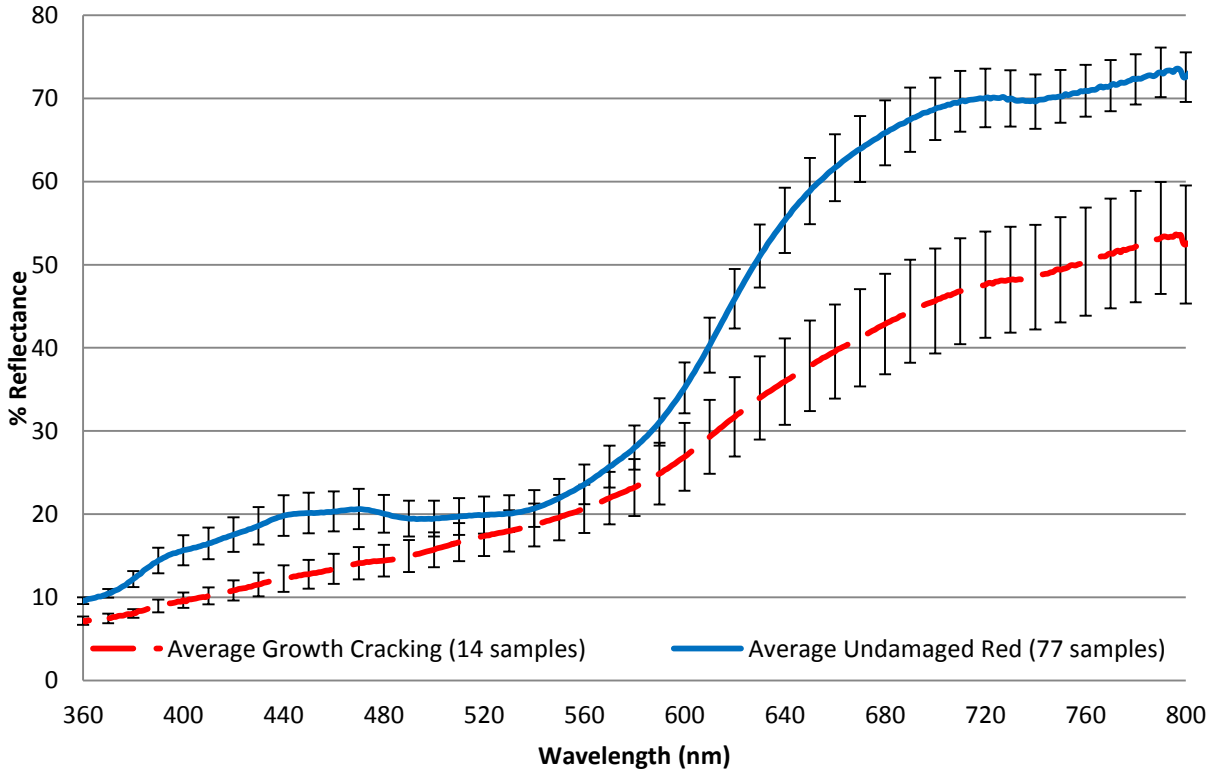

Figure 3-48. 'Red La Soda' Growth Cracking vs. Undamaged- Day of Harvest

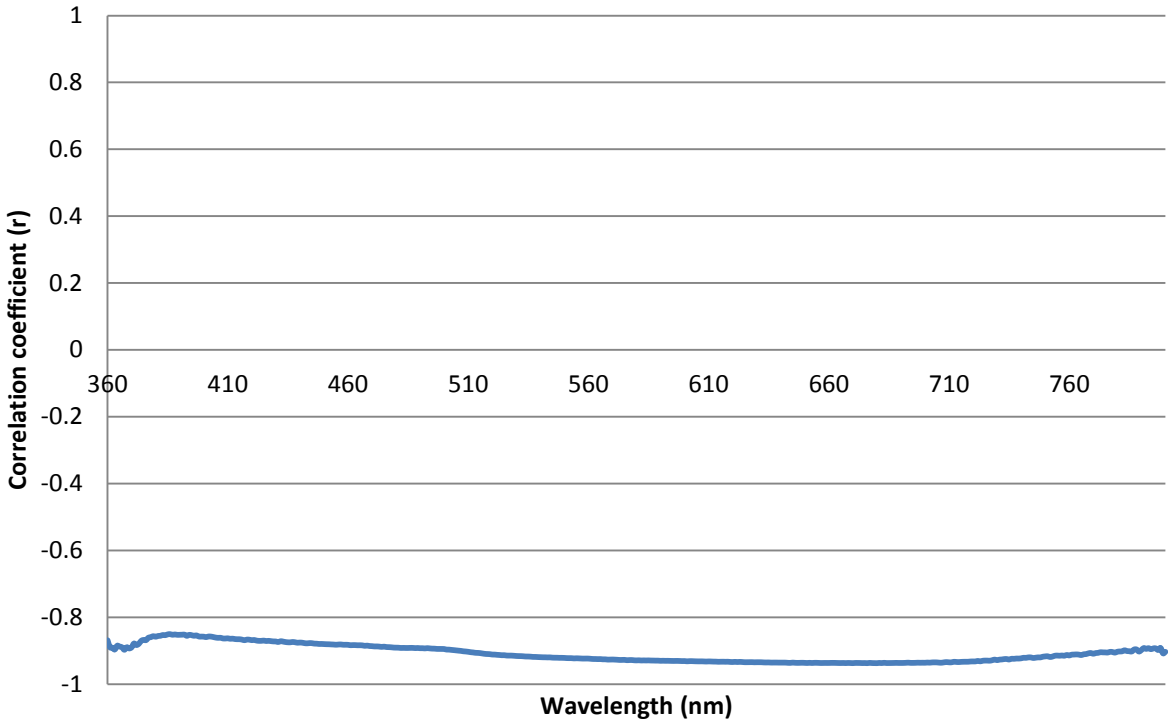

Figure 3-49. 'Fabula' Growth Cracking Correlation coefficients between reflectance at each wavelength and Growth Cracking concentration.

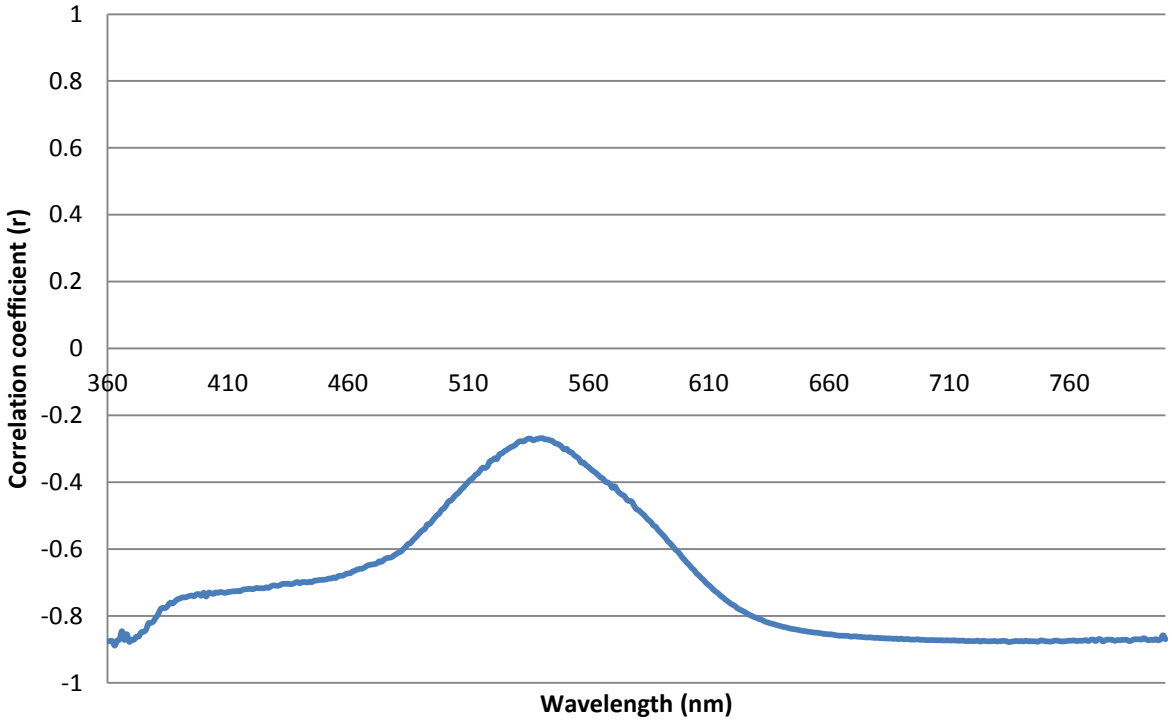

Figure 3-50. 'Red La Soda' Growth Cracking Correlation coefficients between reflectance at each wavelength and Growth Cracking concentration.

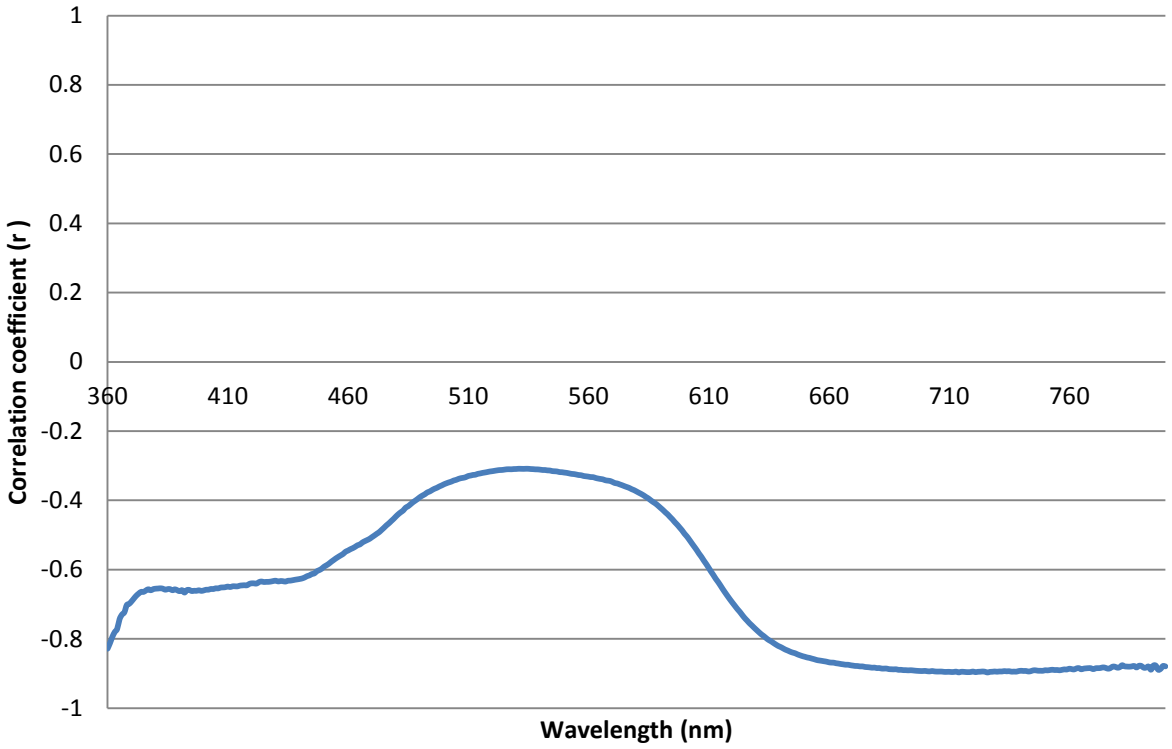

Figure 3-51. Combined Growth Cracking Correlation coefficients between reflectance at each wavelength and Growth Cracking concentration.

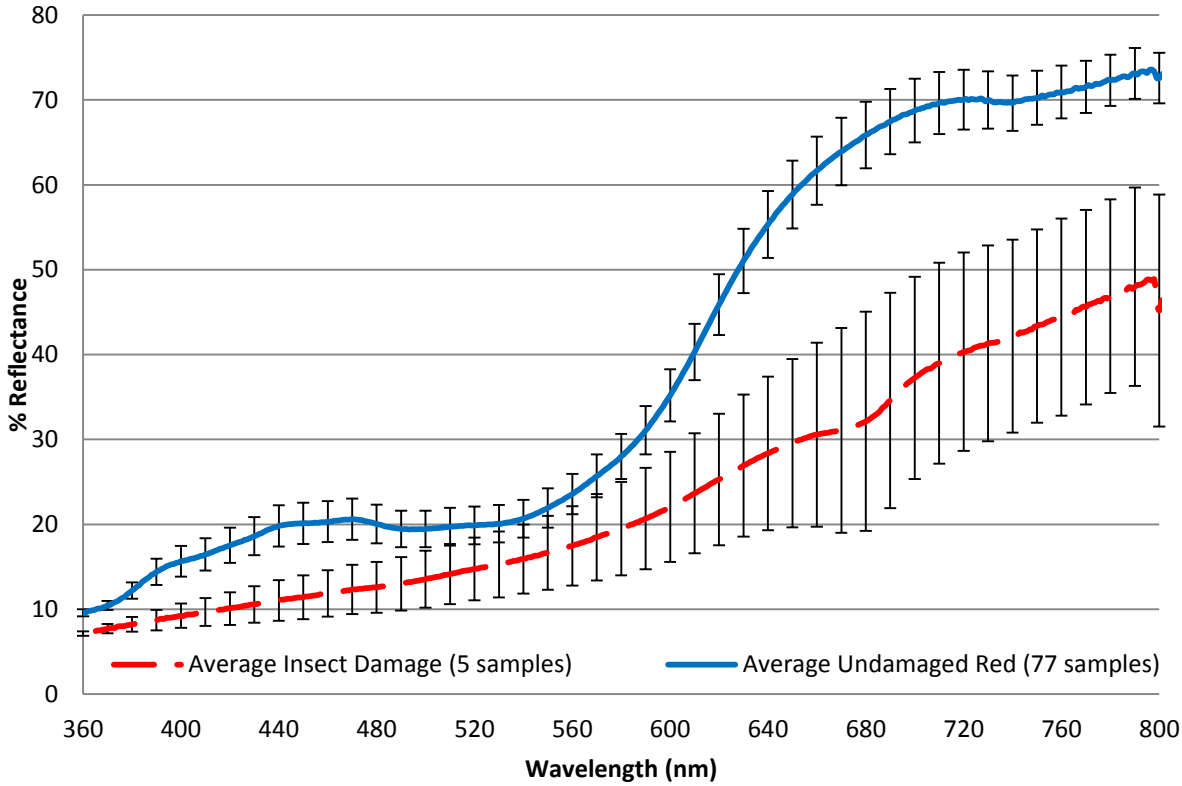

Figure 3-52. 'Red La Soda' Insect Damage vs. Undamaged- Day of Harvest

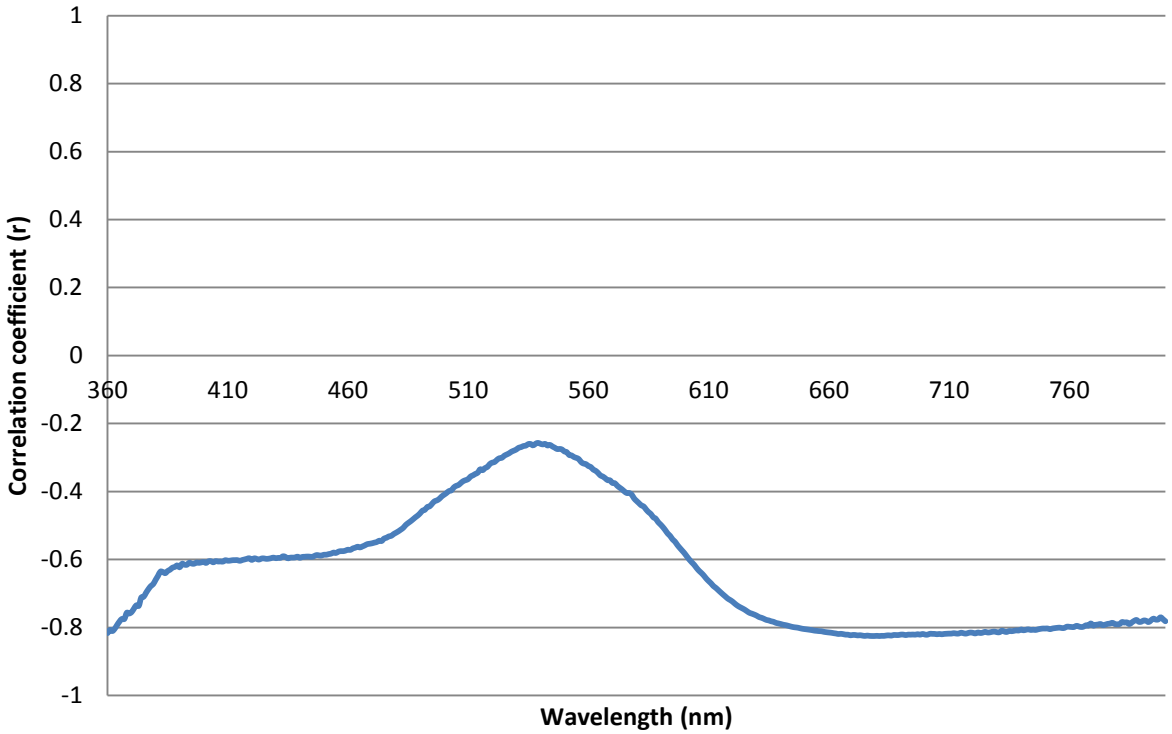

Figure 3-53. 'Red La Soda' Insect Damage Correlation coefficients between reflectance at each wavelength and Growth Cracking concentration.

Table 3-2. Factor results for 'fabula' PLS analysis of sample sets

Disorder	Factors	Dep. variables		Root mean	SEC (%)	SEP (%)	RMSD(%)	RPD	R^2
		Current (%)	Total (%)	PRESS	Calib.	Valid.	Calib.	Valid.	Valid.
Internal bruising	15	1.22	98.82	1.672	1.190	0.991	0.994	3.047	0.993
I.B. 1st der.	5	1.18	99.68	0.782	0.835	0.706	0.698	4.277	0.996
Shatter	4	1.25	98.58	0.138	1.517	1.239	1.235	2.717	0.995
Sh. 1st der.	2	0.66	99.56	0.099	0.852	0.696	0.694	4.838	0.998
Greening	7	0.02	100.00	0.029	0.022	0.017	0.017	101.4	1.000
Gr. 1st der.	2	1.36	99.96	0.111	0.352	0.285	0.281	6.051	1.000
Sunscald	8	0.47	96.05	0.302	1.422	1.154	1.150	2.495	0.984
Sun. 1st der.	4	1.31	99.37	0.318	0.743	0.598	0.601	4.815	0.996
Brown rot	8	0.14	99.04	0.136	1.746	1.340	1.386	3.123	0.991
B.R. 1st der.	3	0.93	99.72	0.166	0.910	0.745	0.741	5.617	0.998
Growth cracking	9	0.50	97.25	0.300	3.102	2.086	2.507	2.373	0.978
G.C. 1st der.	4	0.51	99.68	0.262	0.931	0.784	0.752	4.737	0.997

Table 3-3. Factor results for 'red la soda' PLS analysis of sample sets

Disorder	Factors	Dep. variables		Root mean	SEC (%)	SEP (%)	RMSD(%)	RPD	R^2
		Current (%)	Total (%)	PRESS	Calib.	Valid.	Calib.	Valid.	Valid.
Internal bruising	11	1.346	98.91	0.712	1.411	1.245	1.228	2.005	0.988
I.b. 1st der.	4	2.681	99.09	0.938	1.144	0.960	0.996	2.600	0.993
Shatter	4	0.580	99.70	0.068	0.964	0.936	0.785	3.500	0.998
Sh. 1st der.	2	0.328	99.89	0.089	1.269	1.261	1.034	2.601	0.996
Greening	5	0.095	99.03	0.261	2.399	1.881	1.913	2.776	0.989
Gr. 1st der.	2	2.282	99.97	0.089	0.965	0.771	0.770	4.516	1.000
Sunscald	9	0.717	98.65	0.246	1.630	1.400	1.393	2.137	0.986
Sun. 1st der.	3	2.348	99.25	0.271	1.114	0.957	0.952	3.126	0.995
Brown rot	10	0.230	98.80	0.215	1.625	1.267	1.323	3.622	0.991
B.R. 1st der.	4	0.401	99.71	0.208	1.004	0.822	0.818	5.583	0.998
Growth cracking	11	0.709	97.60	0.356	2.663	2.120	2.162	2.406	0.995
G.C. 1st der.	5	0.512	99.57	0.294	1.312	1.071	1.065	3.572	0.994
Insect damage	12	0.804	97.74	0.555	1.638	1.216	1.292	1.354	0.992
I.D. 1st der.	3	5.326	98.32	0.422	1.247	0.988	0.983	1.666	0.998

Table 3-4. Factor results for combined varieties PLS analysis of sample sets

Disorder	Factors	Dep. variables		Root Mean	SEC (%)	SEP (%)	RMSD(%)	RPD	R^2
		Current (%)	Total (%)	PRESS	Calib.	Valid.	Calib.	Valid.	Valid.
Internal bruising	15	1.922	93.65	1.128	3.420	2.847	2.857	1.378	0.966
I.B. 1st der.	7	0.441	98.77	0.942	1.760	1.487	1.470	2.639	0.990
Shatter	5	0.205	98.78	0.126	2.070	1.678	1.686	2.802	0.995
Sh. 1st der.	2	23.27	97.83	0.550	2.396	1.783	1.952	2.637	0.974
Greening	7	0.191	99.43	0.110	1.907	1.511	1.521	3.251	0.997
Gr. 1st der.	3	1.989	99.78	0.107	1.263	1.003	1.007	4.898	0.998
Sunscald	15	0.402	97.65	0.337	2.500	2.028	2.020	2.048	0.977
Sun. 1st der.	6	0.835	98.46	0.343	1.821	1.476	1.472	2.814	0.989
Brown rot	15	0.201	99.30	0.084	2.358	1.878	1.872	3.064	0.992
B.r. 1st der.	4	0.899	99.07	0.193	2.842	2.314	2.314	4.210	0.999
Growth cracking	15	0.318	98.24	0.279	3.654	3.039	2.953	2.340	0.979
G.C. 1st der.	6	0.765	98.87	0.325	2.400	1.949	1.939	3.649	0.990

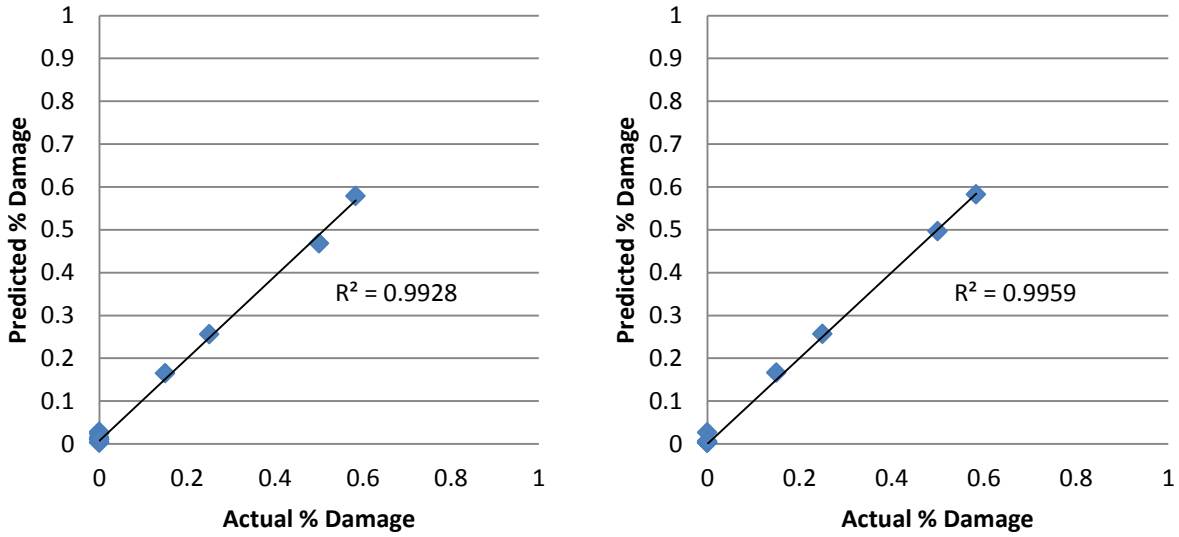

Figure 3-54. Damage Prediction Using PLS 'Fabula' Internal Bruising Reflectance (left), 1st Derivative (right)

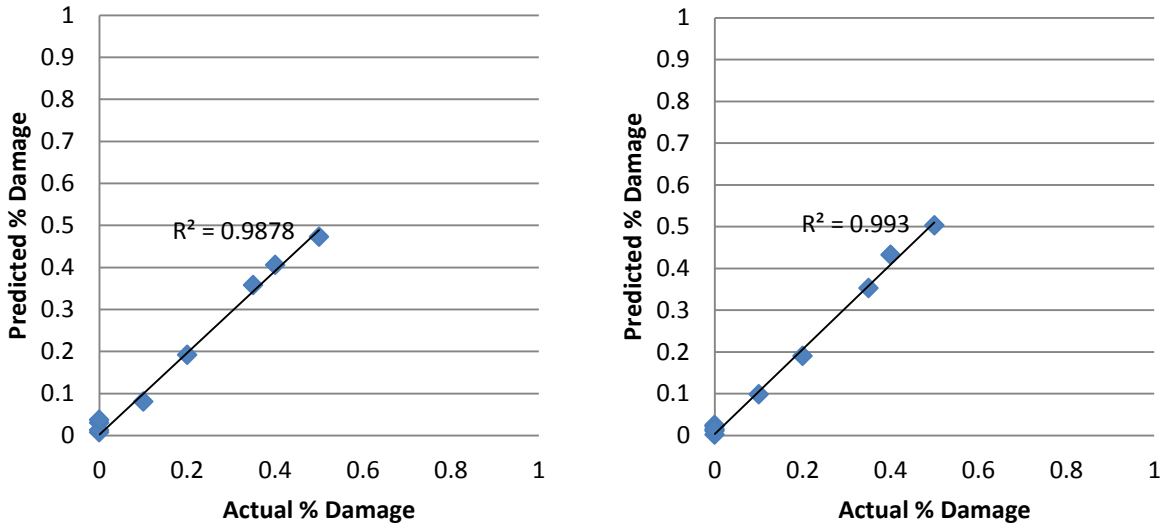

Figure 3-55. Damage Prediction Using PLS 'Red La Soda' Internal Bruising Reflectance (left), 1st Derivative (right)

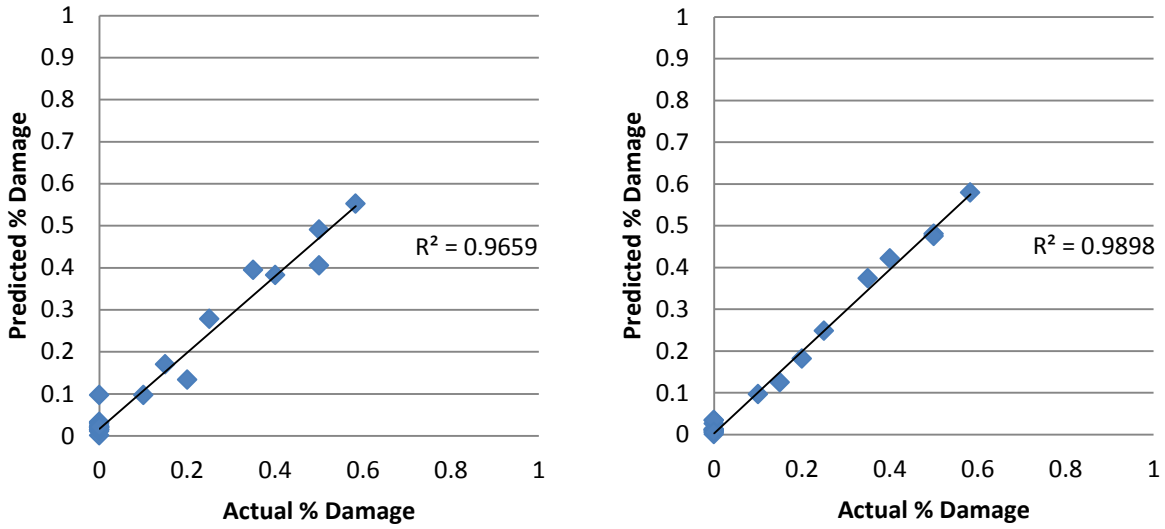

Figure 3-56. Damage Prediction Using PLS Combined Internal Bruising Reflectance (left), 1st Derivative (right)

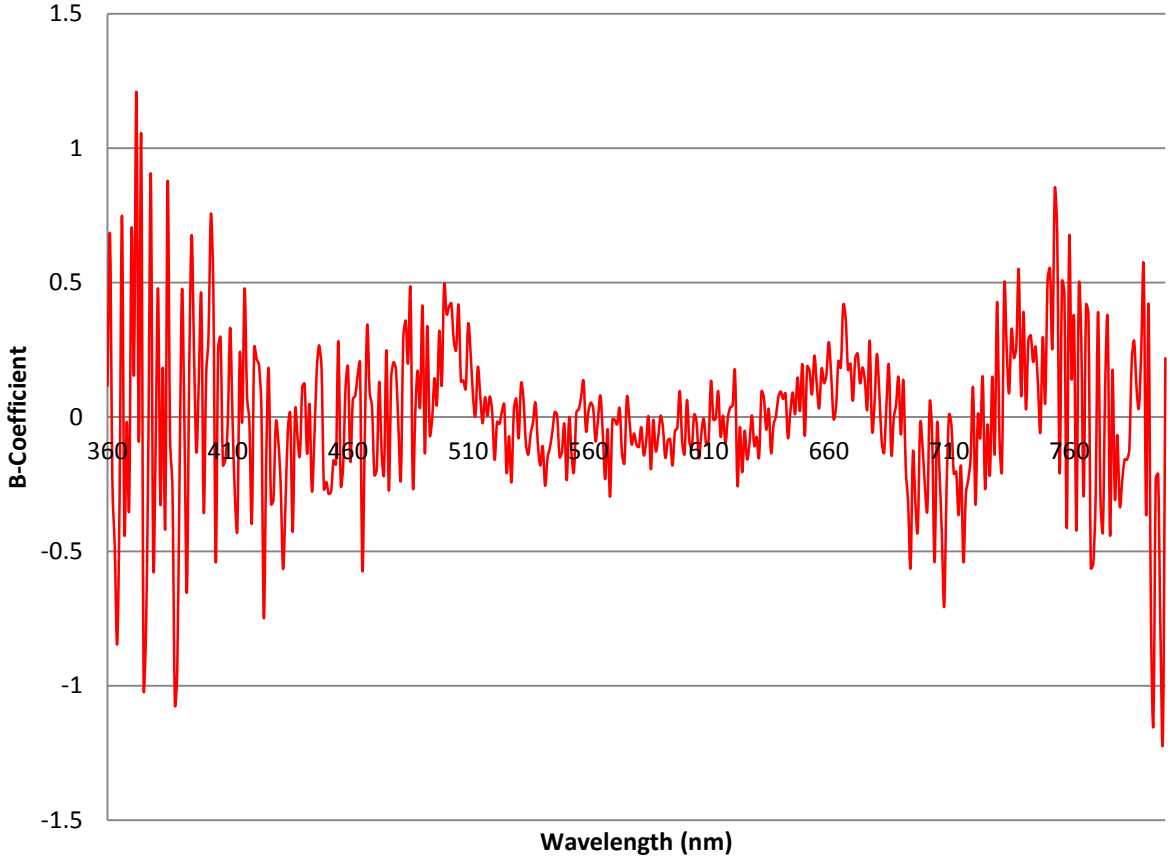

Figure 3-57. B-Coefficients 'Fabula' Internal Bruising Reflectance

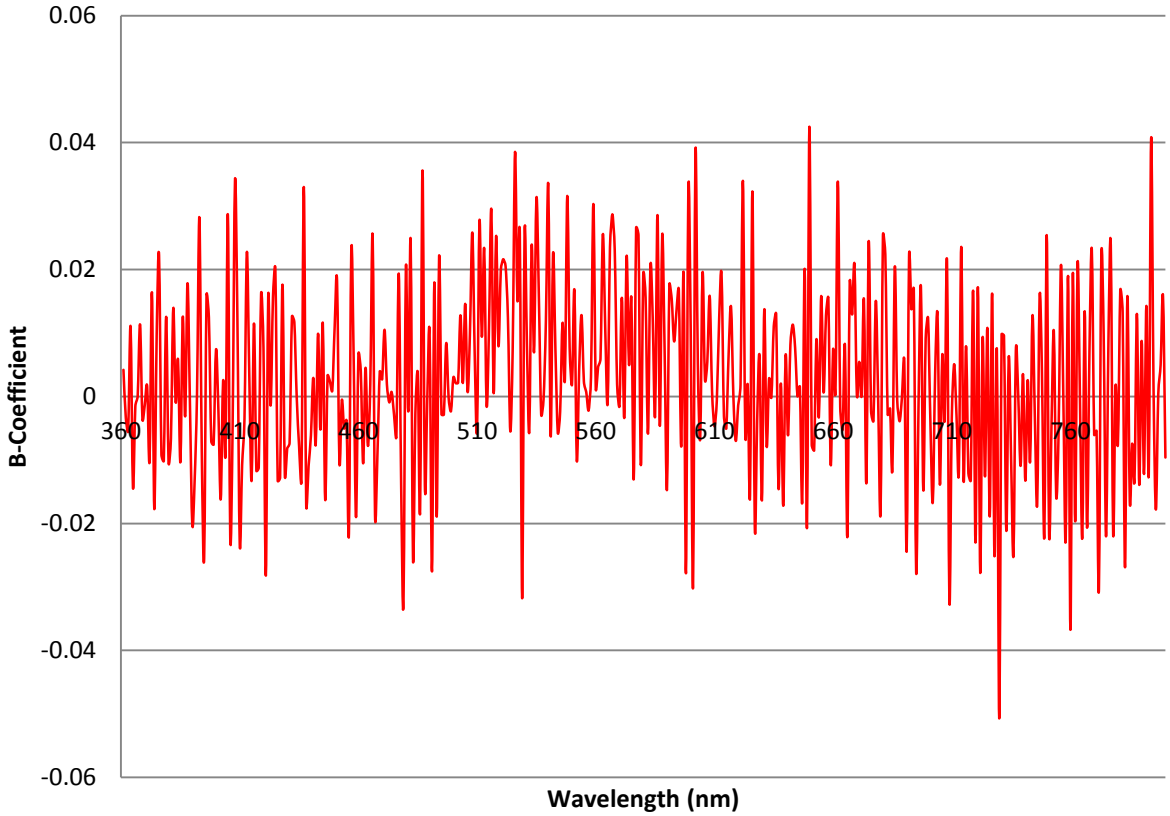

Figure 3-58. B-Coefficients 'Fabula' Internal Bruising 1st Derivative Reflectance

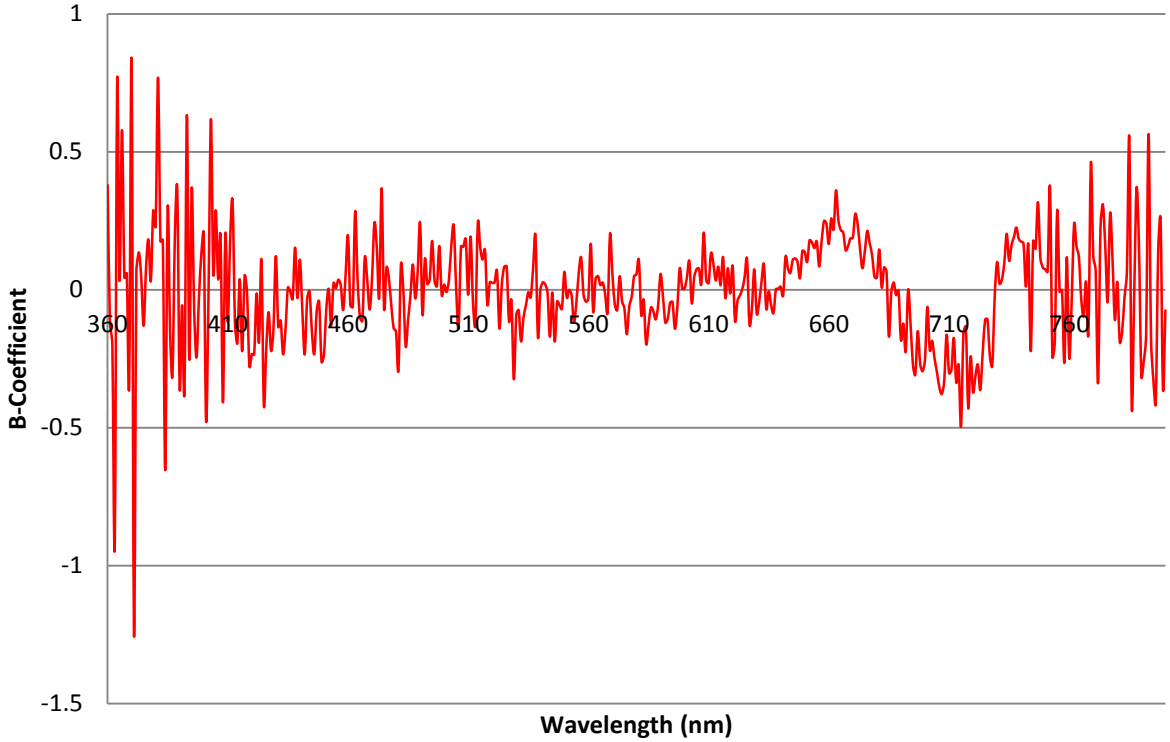

Figure 3-59. B-Coefficients 'Red La Soda' Internal Bruising Reflectance

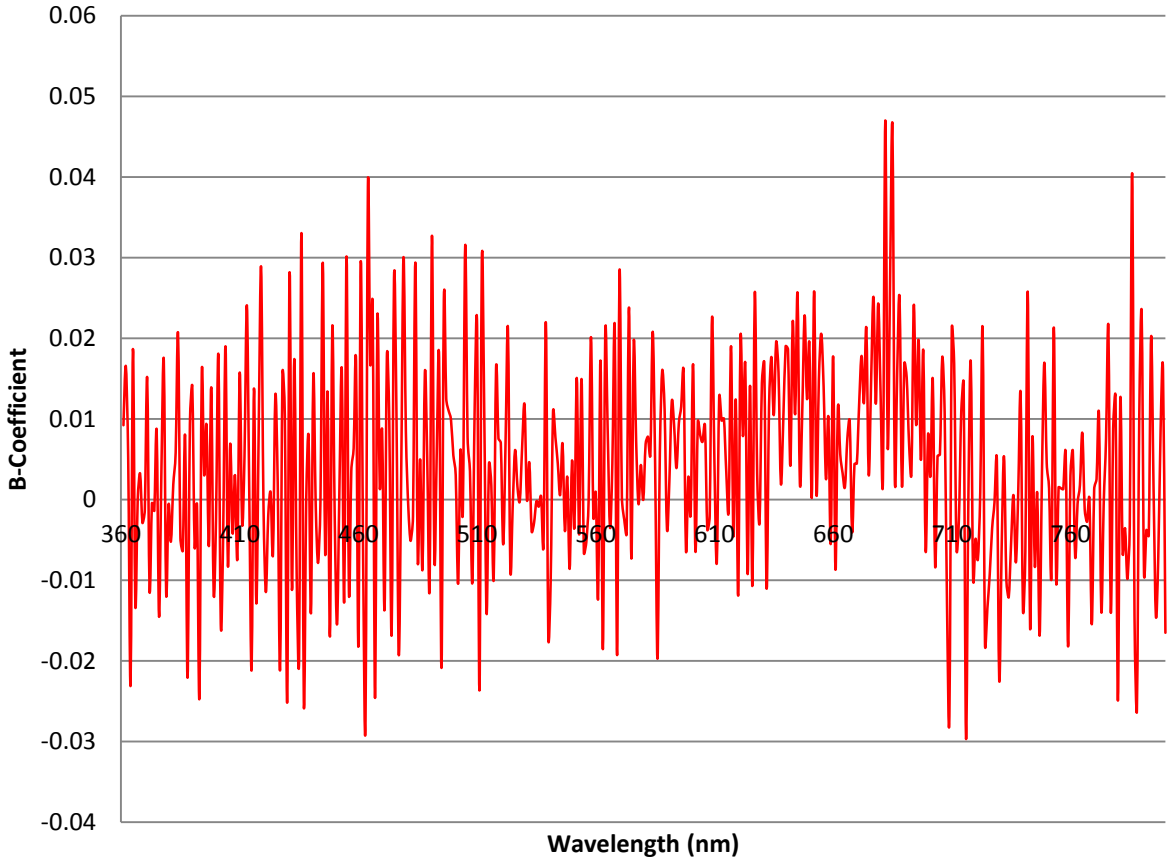

Figure 3-60. B-Coefficients 'Red La Soda' Internal Bruising 1st Derivative Reflectance

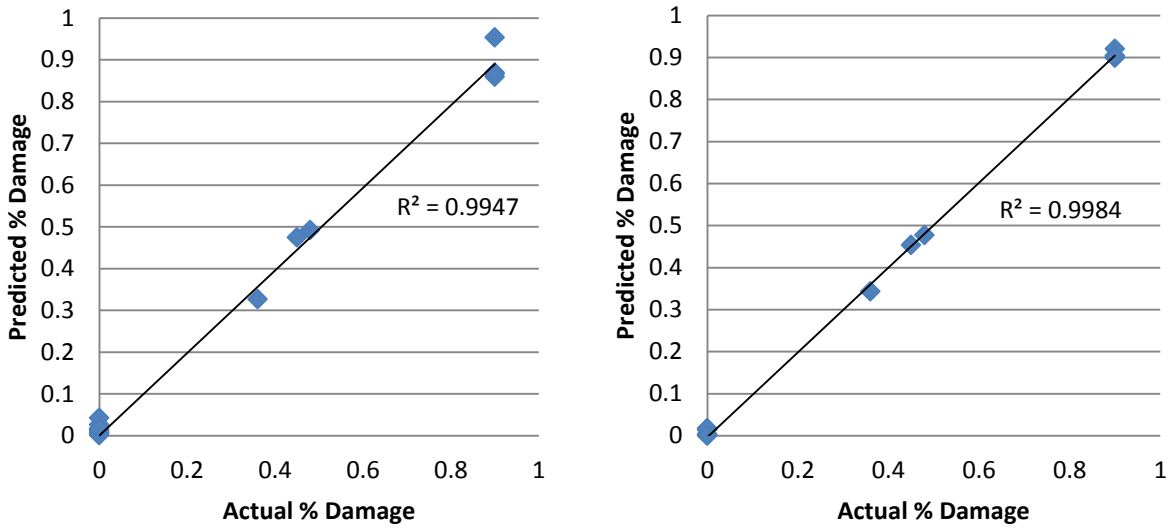

Figure 3-61. Damage Prediction Using PLS 'Fabula' Shatter Reflectance (left), 1st Derivative (right)

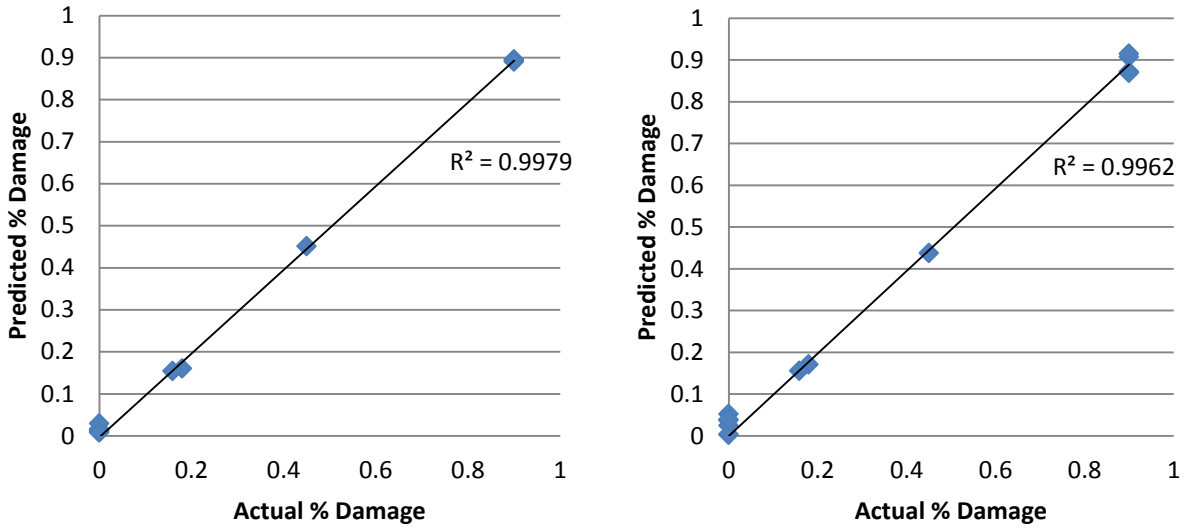

Figure 3-62. Damage Prediction Using PLS 'Red La Soda' Shatter Reflectance (left), 1st Derivative (right)

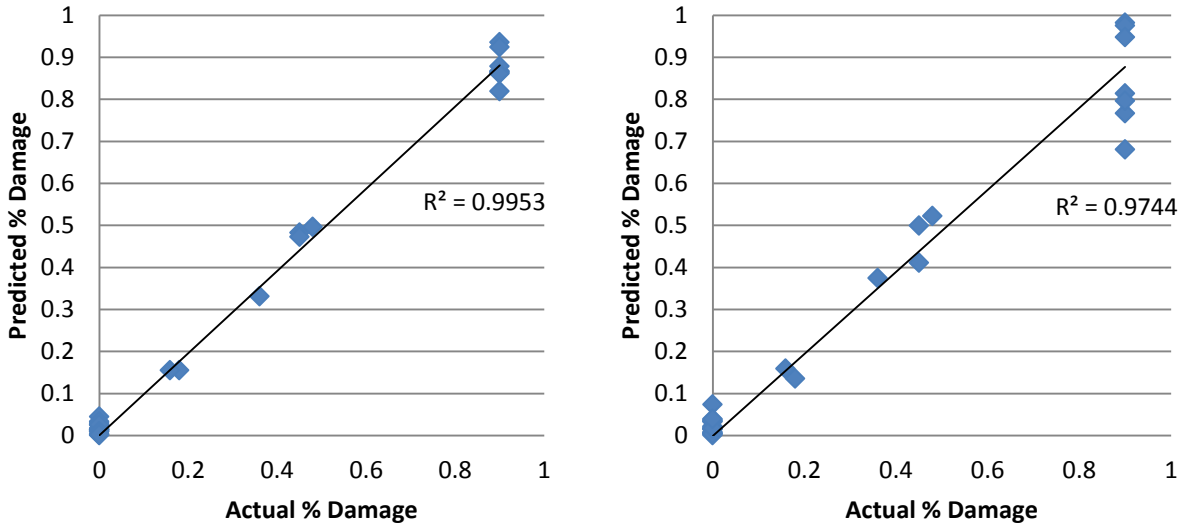

Figure 3-63. Damage Prediction Using PLS Combined Shatter Reflectance (left), 1st Derivative (right)

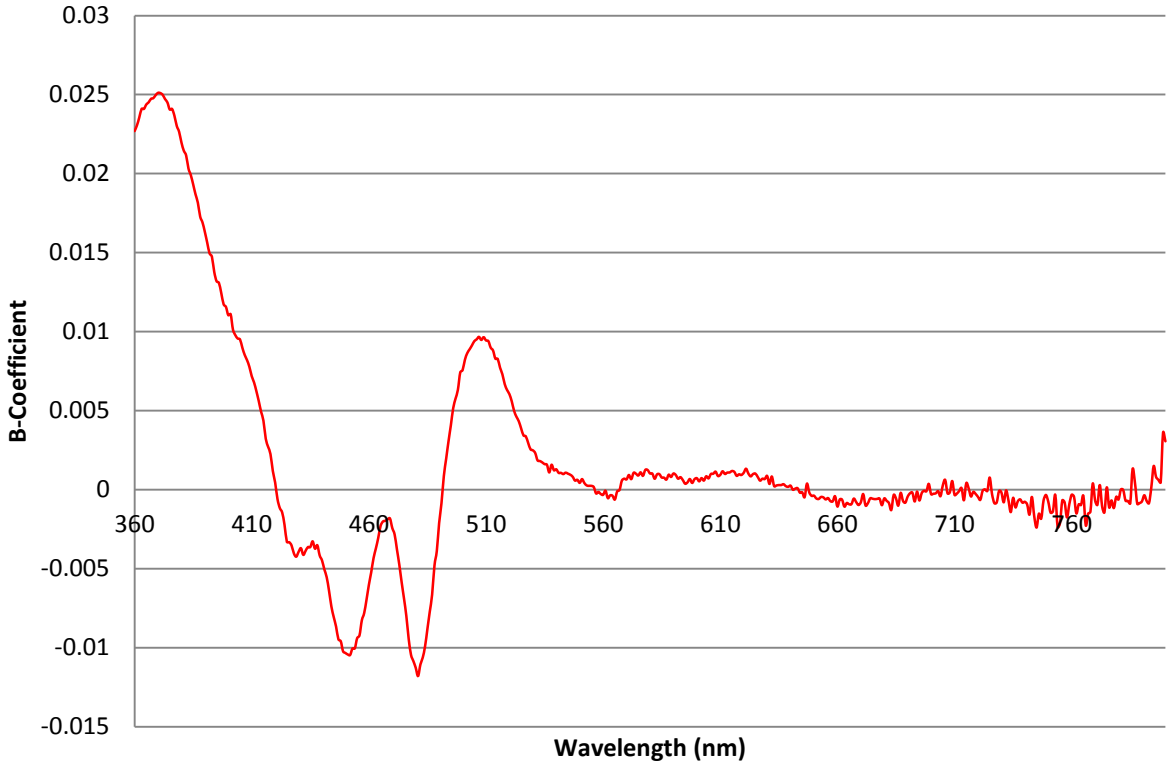

Figure 3-64. B-Coefficients 'Fabula' Shatter Reflectance

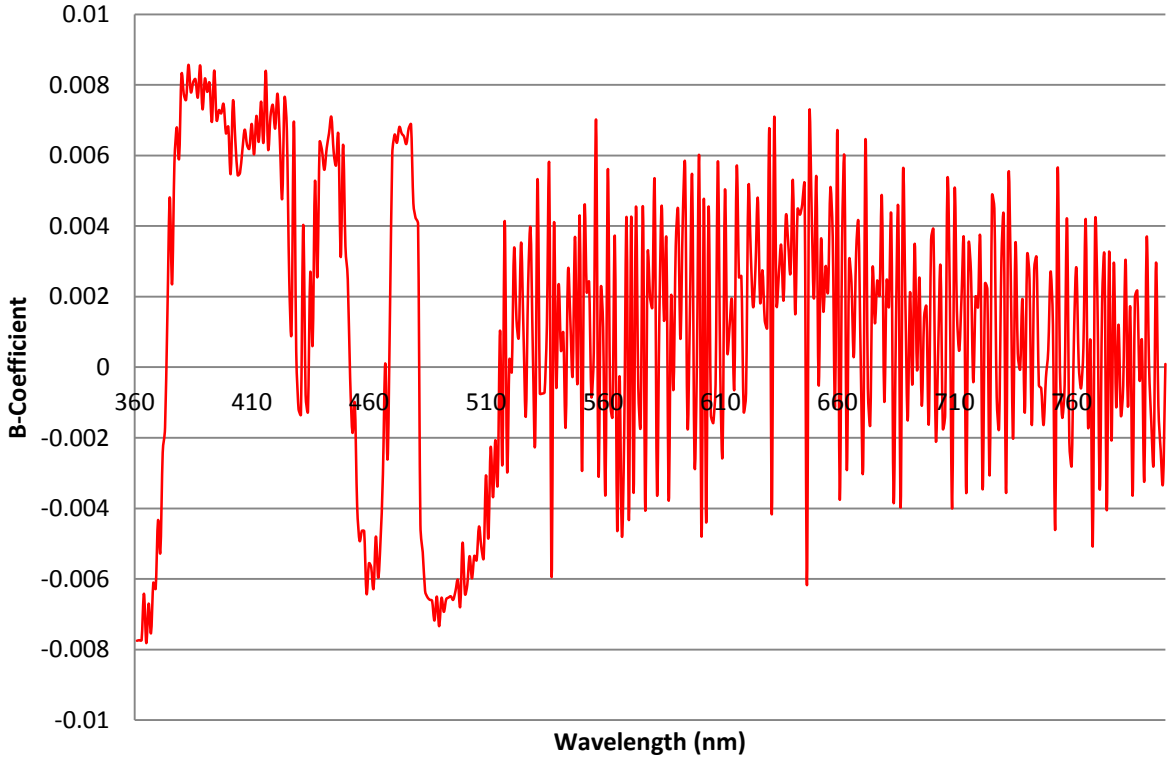

Figure 3-65. B-Coefficients 'Fabula' Shatter 1st Derivative Reflectance

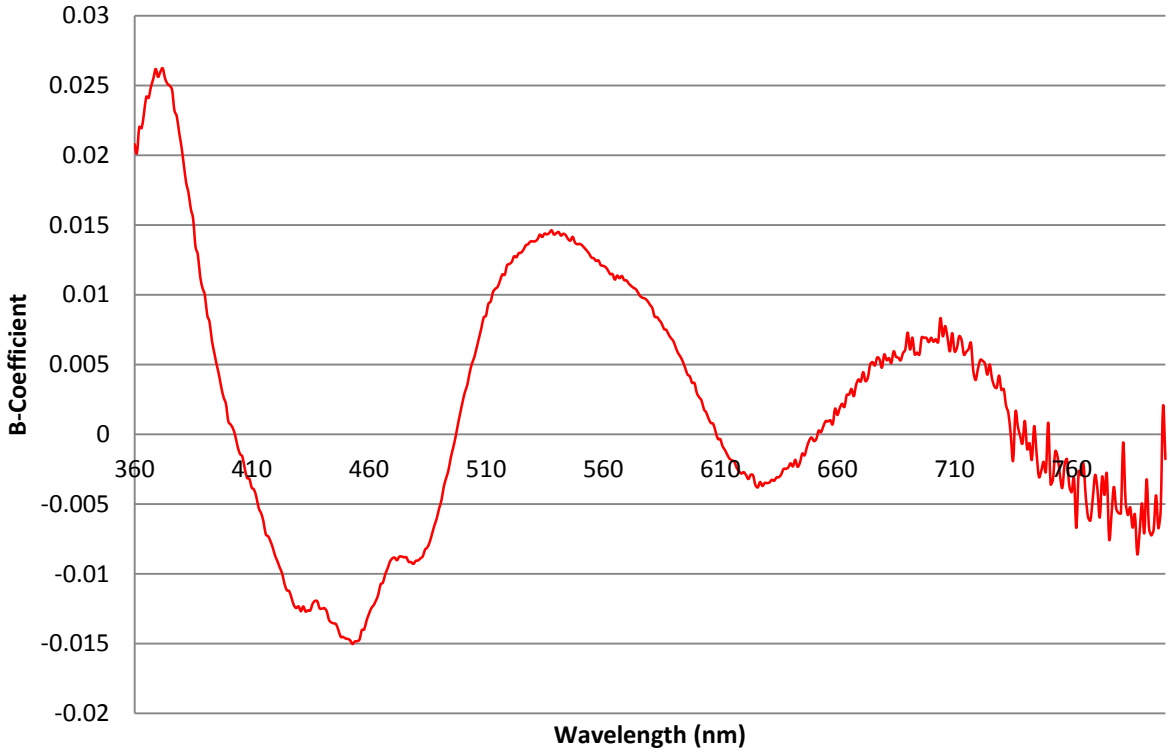

Figure 3-66. B-Coefficients 'Red La Soda' Shatter Reflectance

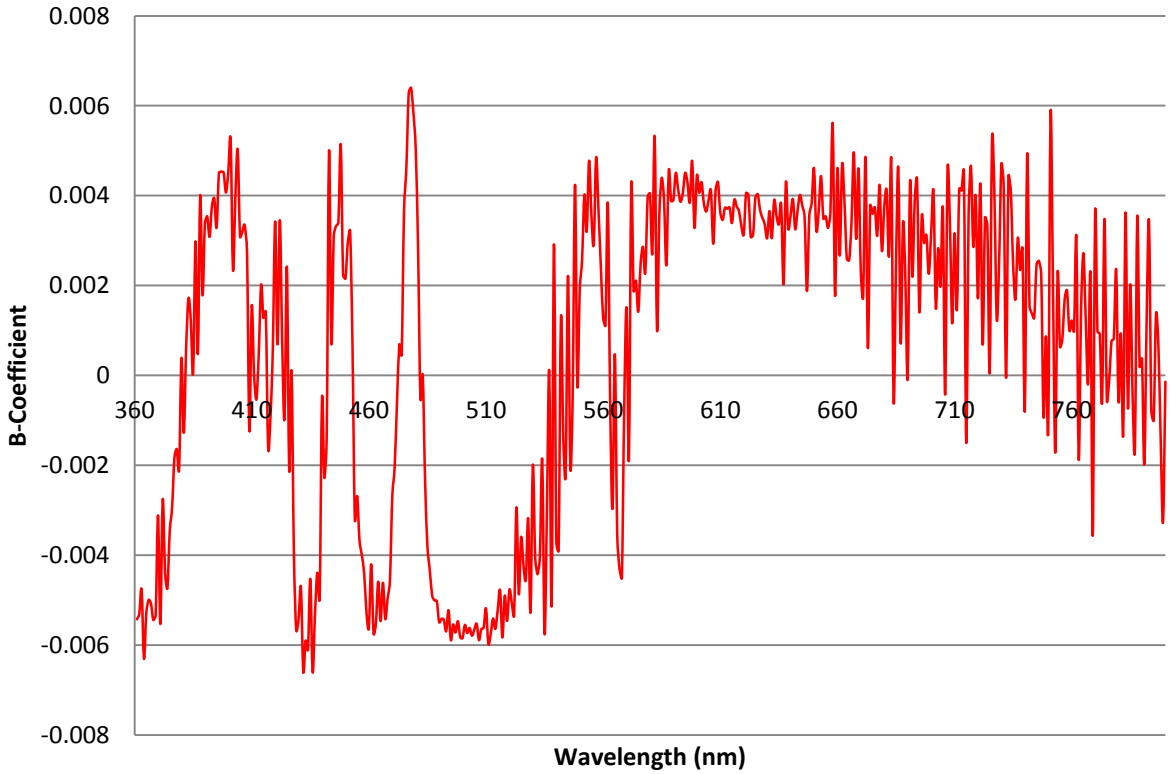

Figure 3-67. B-Coefficients 'Red La Soda' Shatter 1st Derivative Reflectance

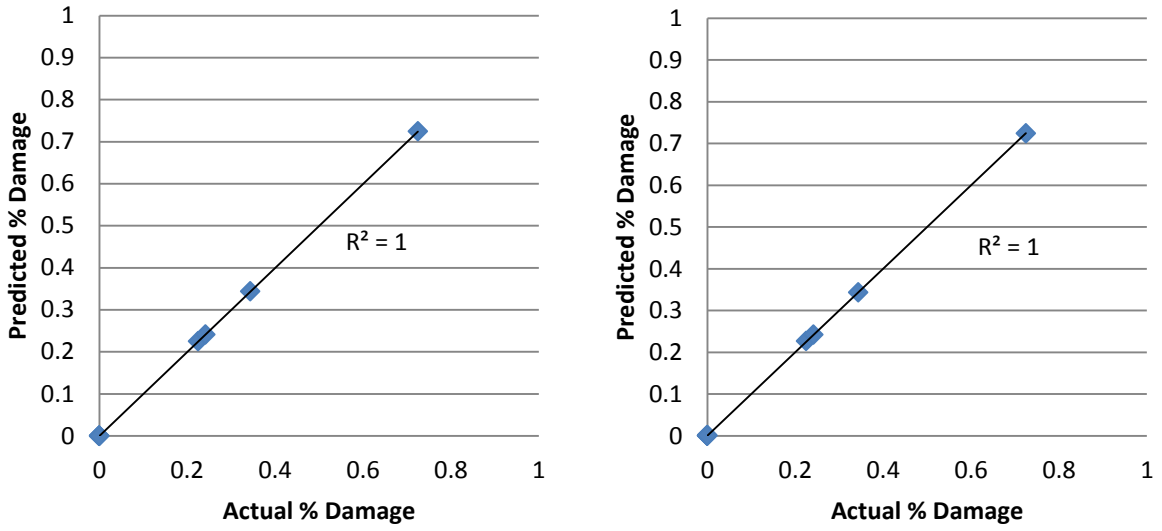

Figure 3-68. Damage Prediction Using PLS 'Fabula' Greening Reflectance (left), 1st Derivative (right)

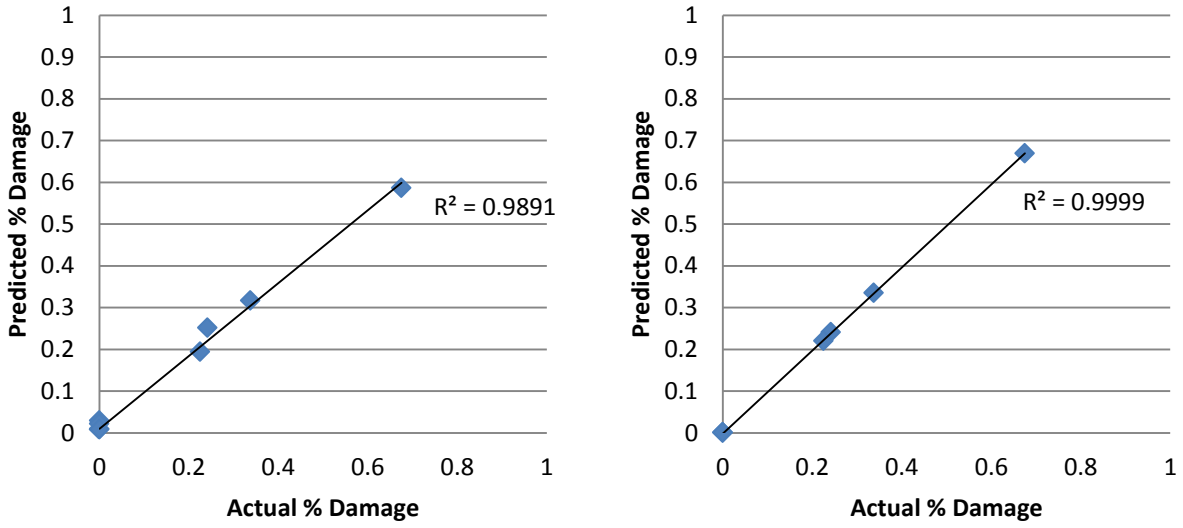

Figure 3-69. Damage Prediction Using PLS 'Red La Soda' Greening Reflectance (left), 1st Derivative (right)

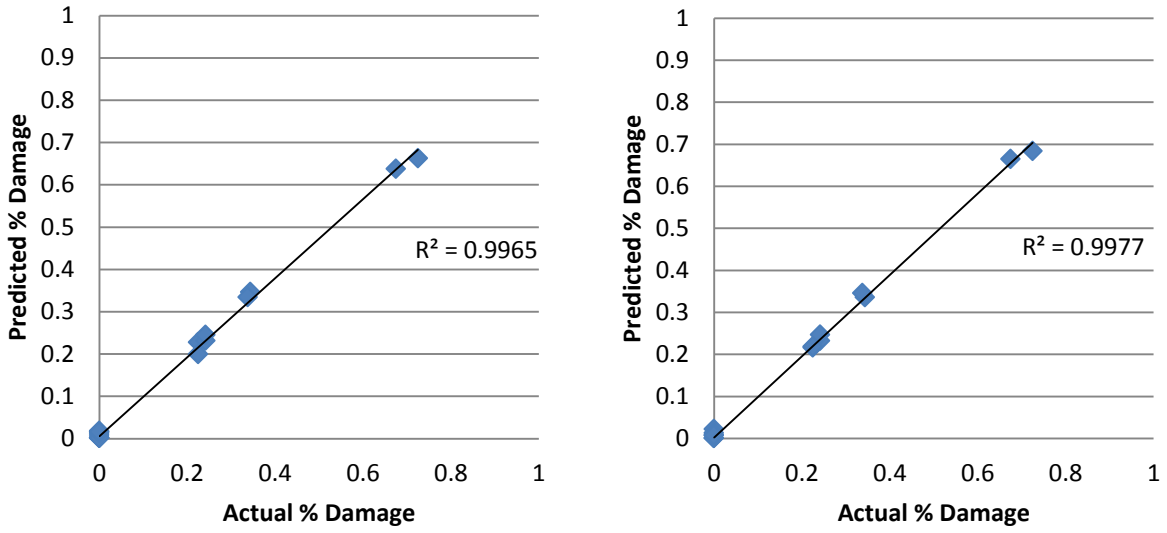

Figure 3-70. Damage Prediction Using PLS Combined Greening Reflectance (left), 1st Derivative (right)

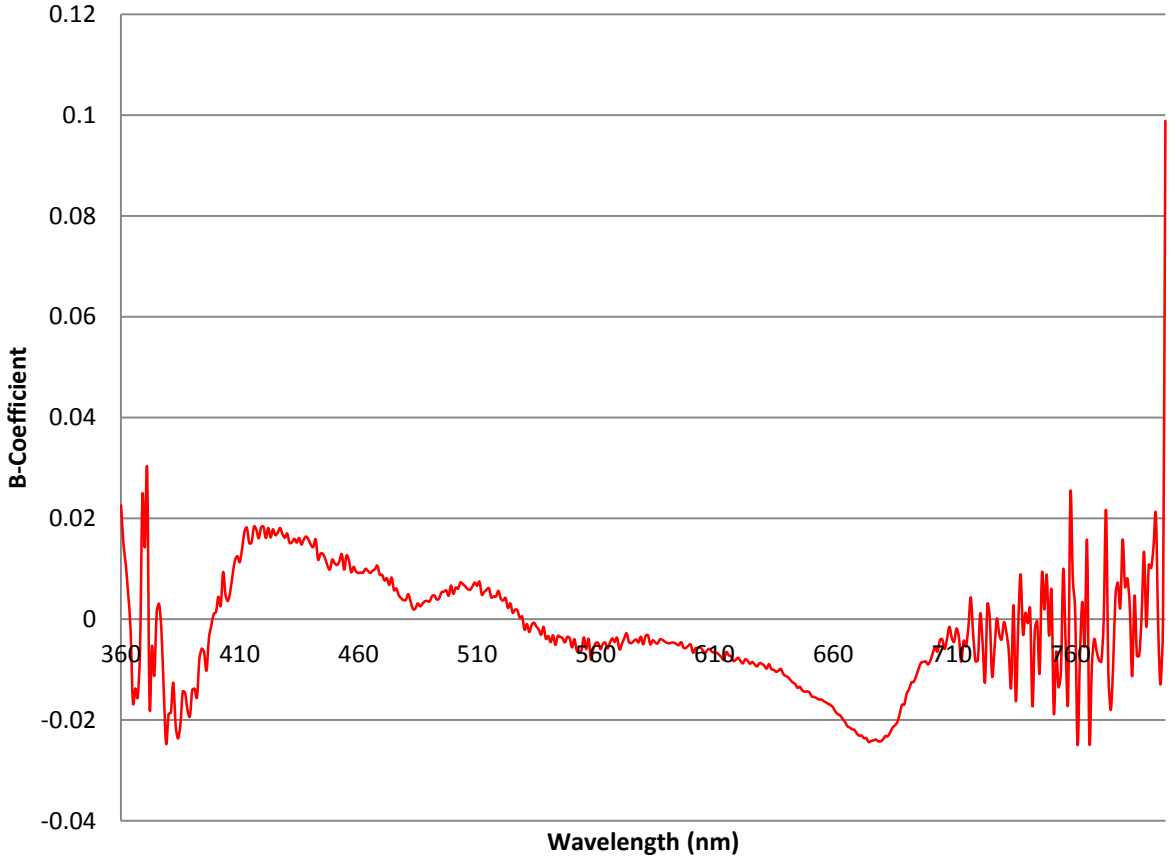

Figure 3-71. B-Coefficients 'Fabula' Greening Reflectance

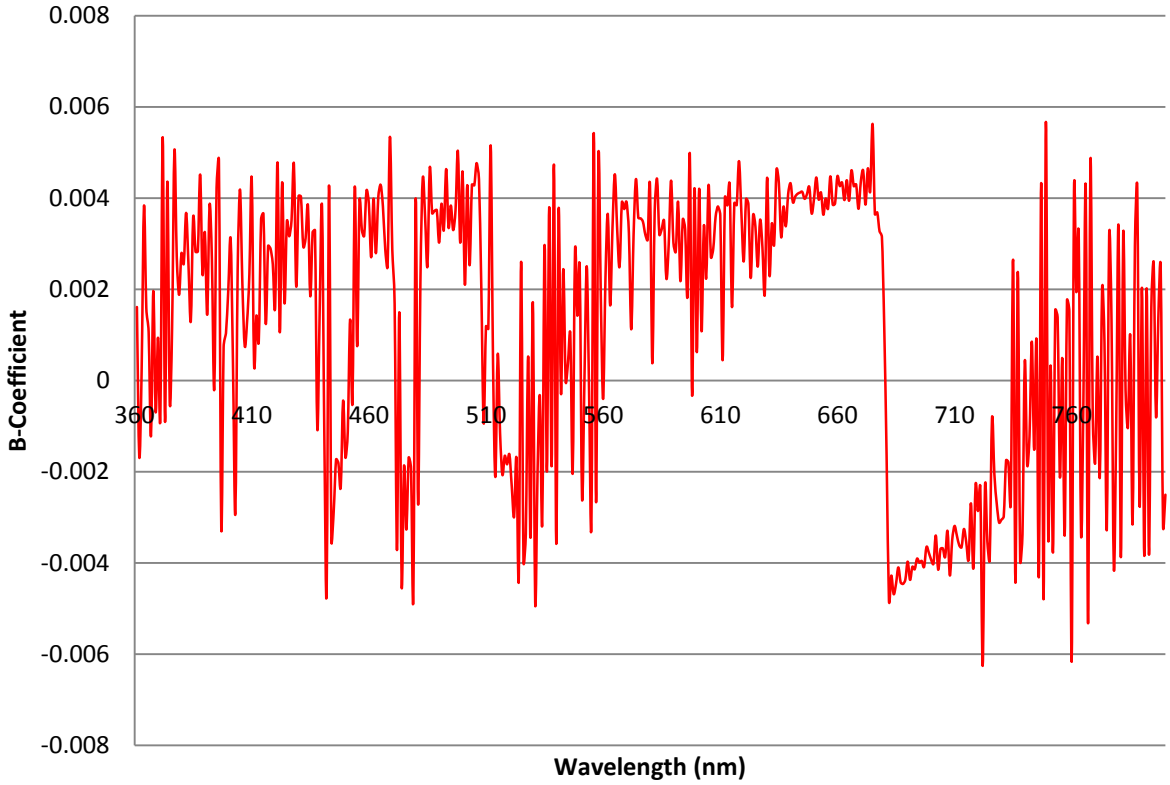

Figure 3-72. B-Coefficients 'Fabula' Greening 1st Derivative Reflectance

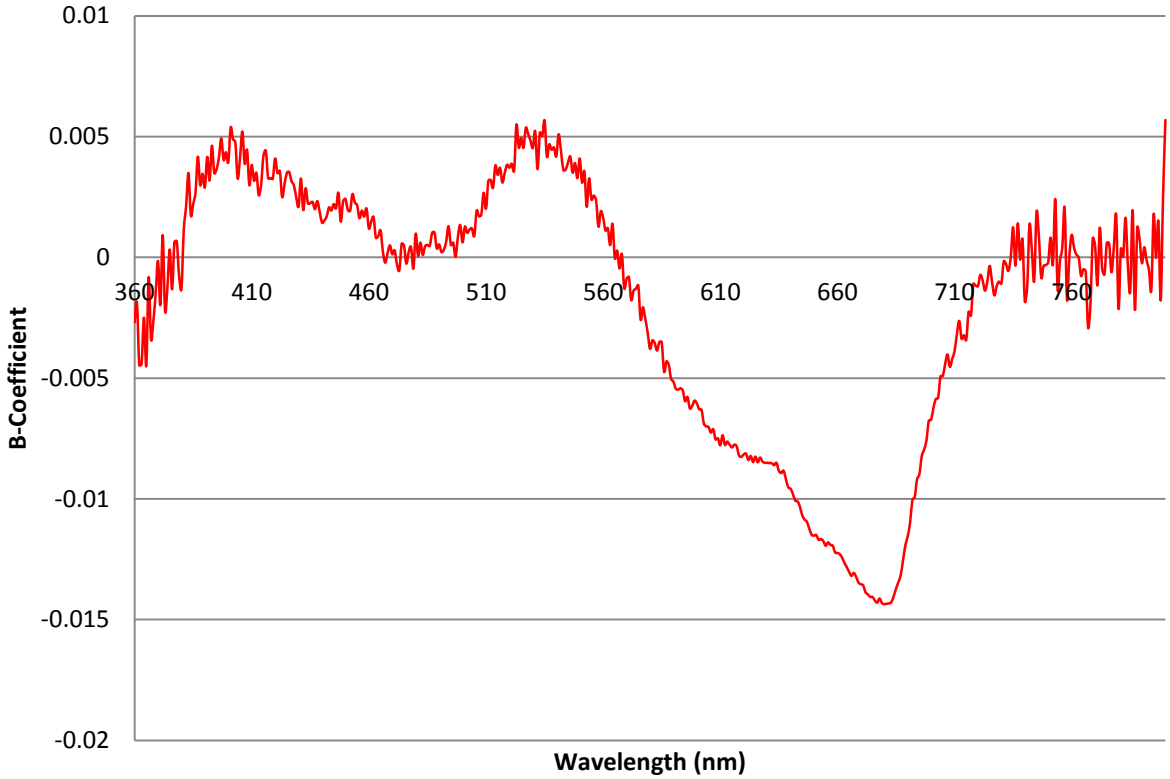

Figure 3-73. B-Coefficients 'Red La Soda' Greening Reflectance

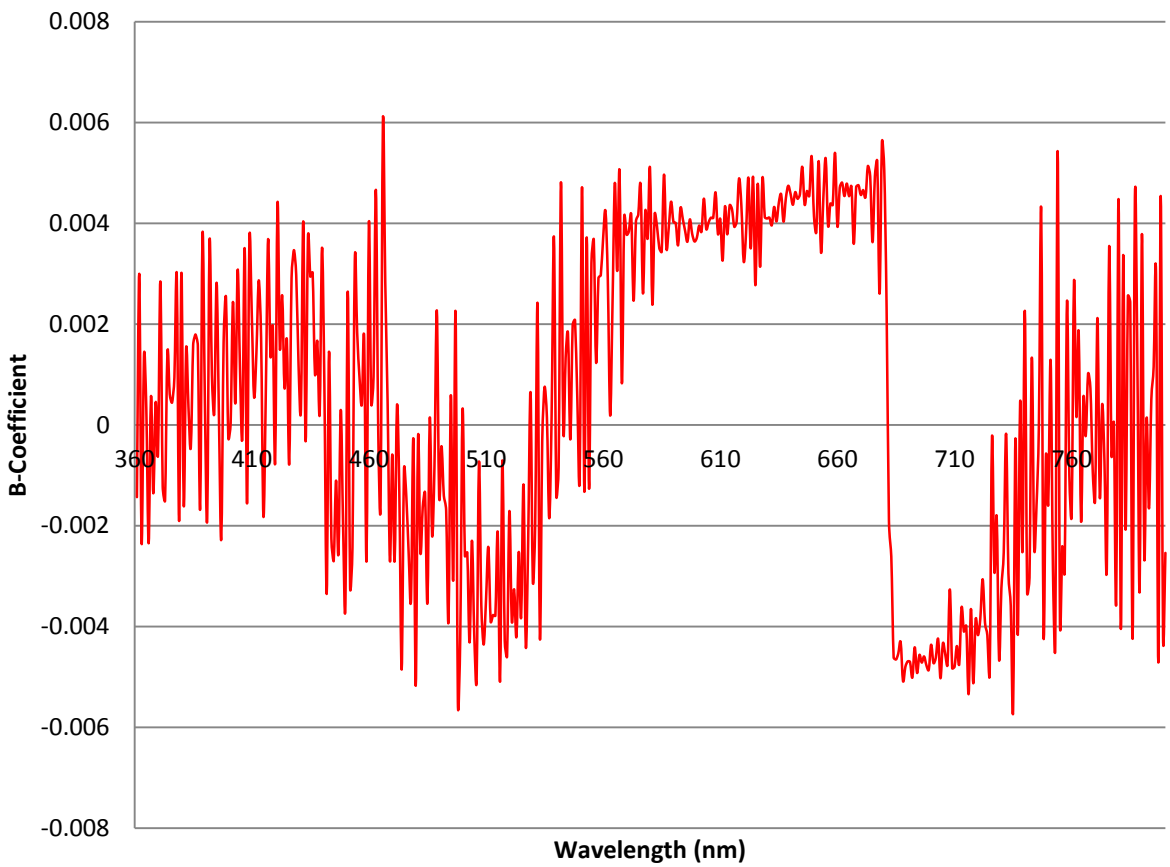

Figure 3-74. B-Coefficients 'Red La Soda' Greening 1st Derivative Reflectance

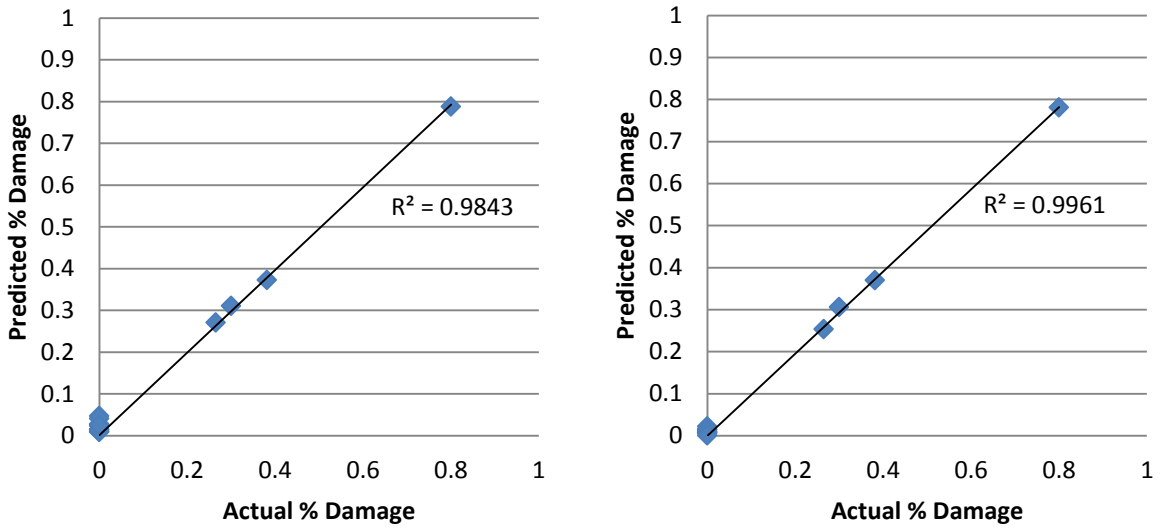

Figure 3-75. Damage Prediction Using PLS 'Fabula' Sunscald Reflectance (left), 1st Derivative (right)

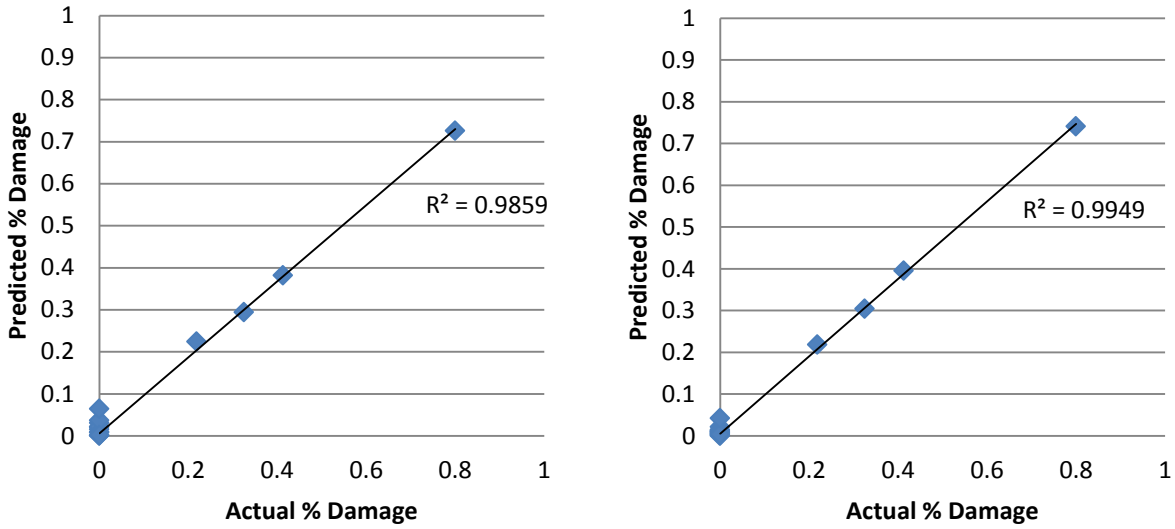

Figure 3-76. Damage Prediction Using PLS 'Red La Soda' Sunscald Reflectance (left), 1st Derivative (right)

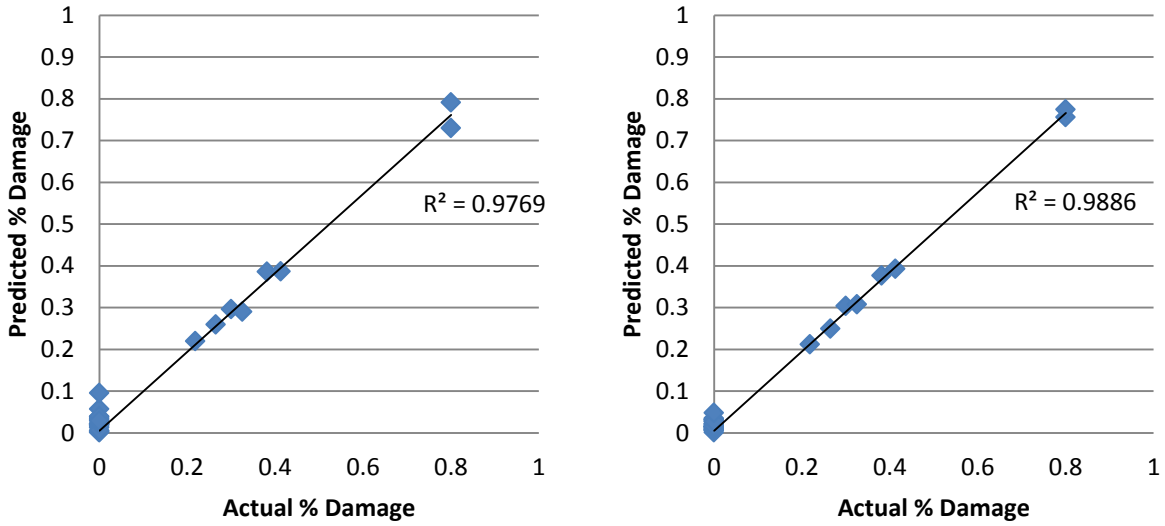

Figure 3-77. Damage Prediction Using PLS Combined Sunscald Reflectance (left), 1st Derivative (right)

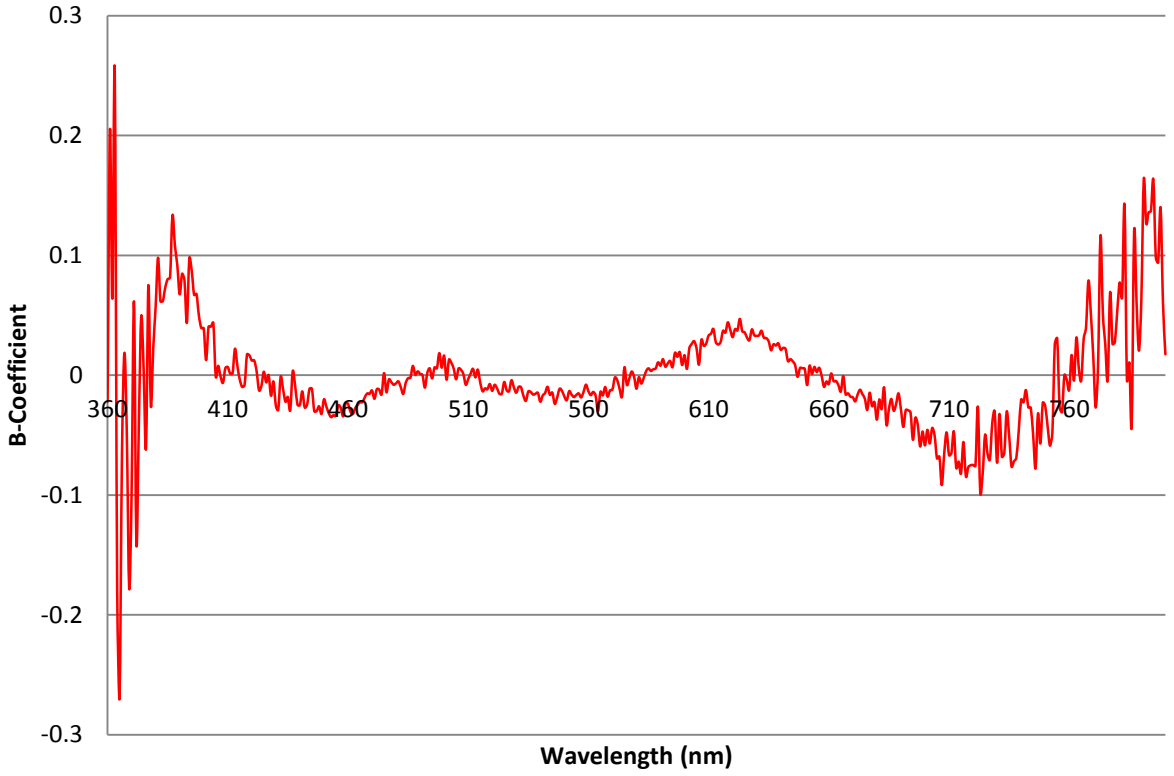

Figure 3-78. B-Coefficients 'Fabula' Sunscald Reflectance

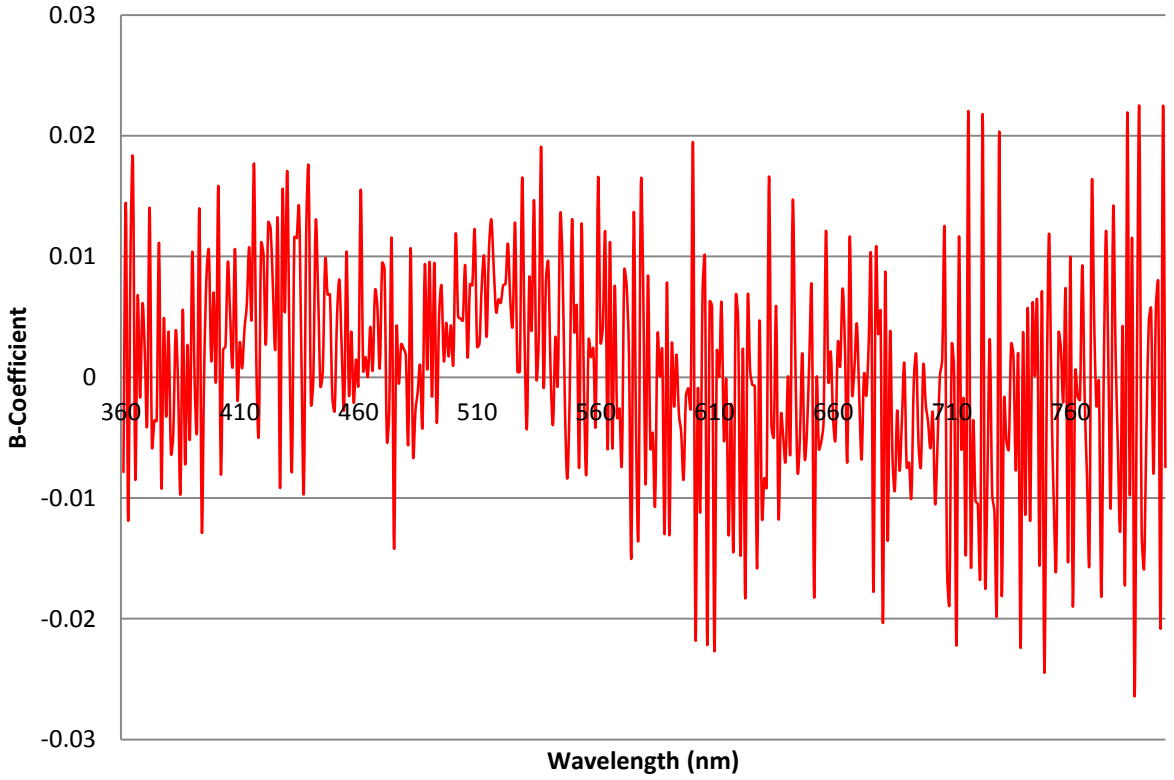

Figure 3-79. B-Coefficients 'Fabula' Sunscald 1st Derivative Reflectance

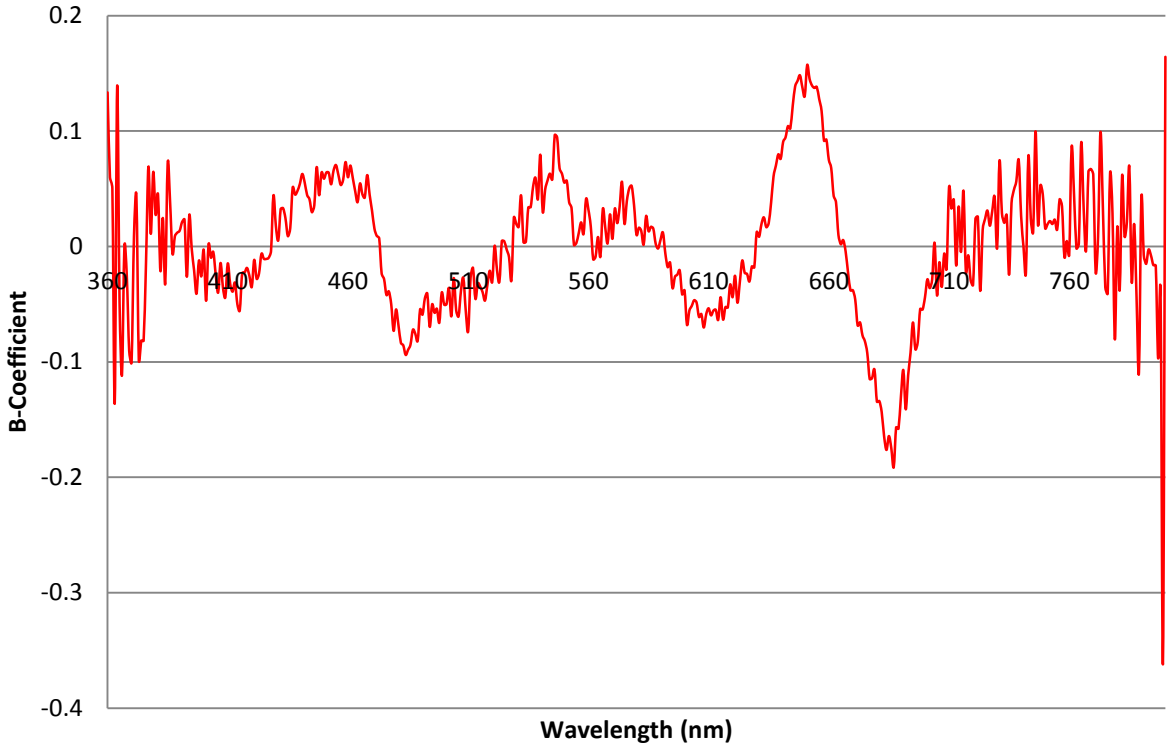

Figure 3-80. B-Coefficients 'Red La Soda' Sunscald Reflectance

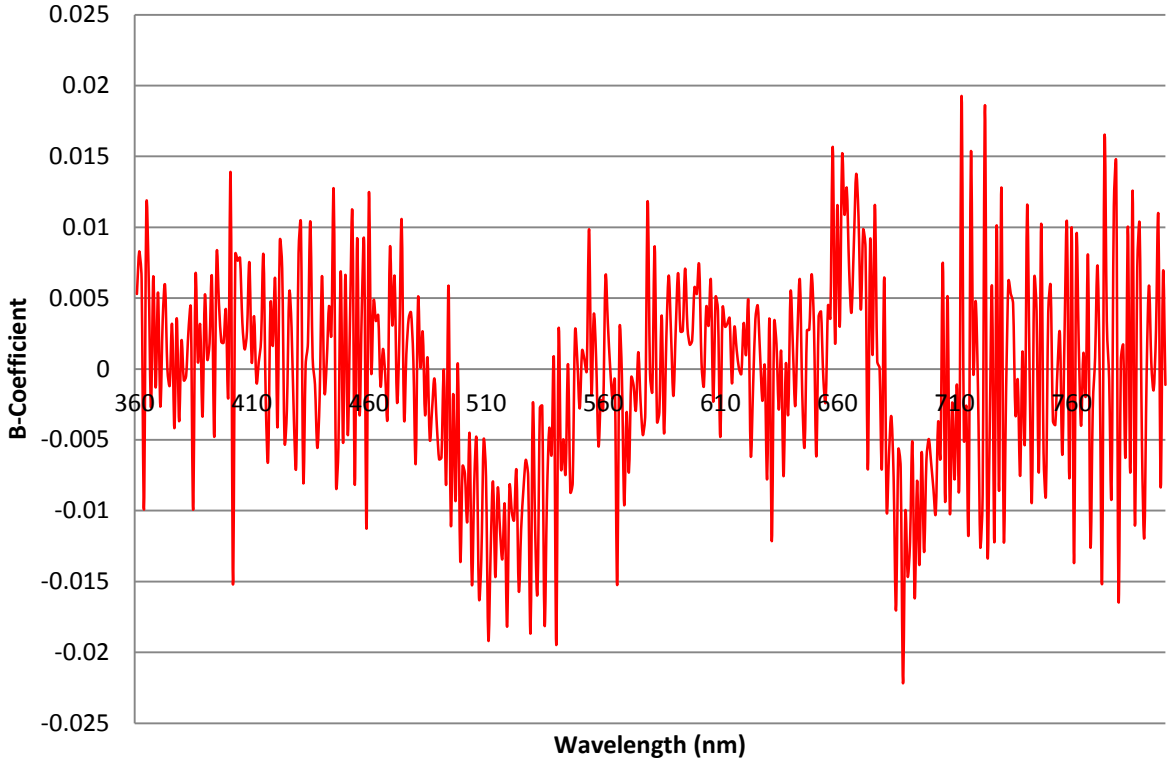

Figure 3-81. B-Coefficients 'Red La Soda' Sunscald 1st Derivative Reflectance

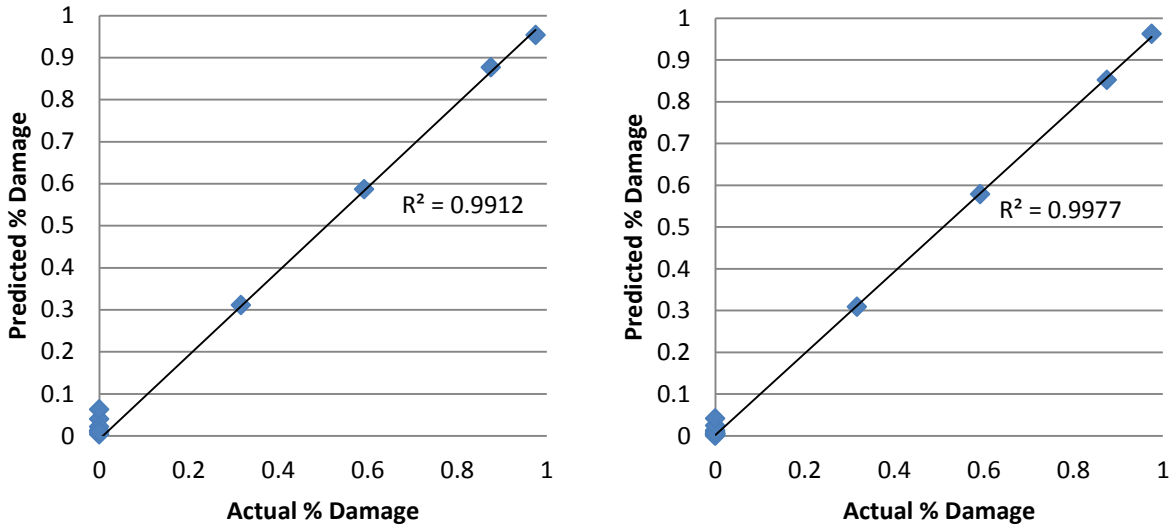

Figure 3-82. Damage Prediction Using PLS 'Fabula' Brown Rot Reflectance (left), 1st Derivative (right)

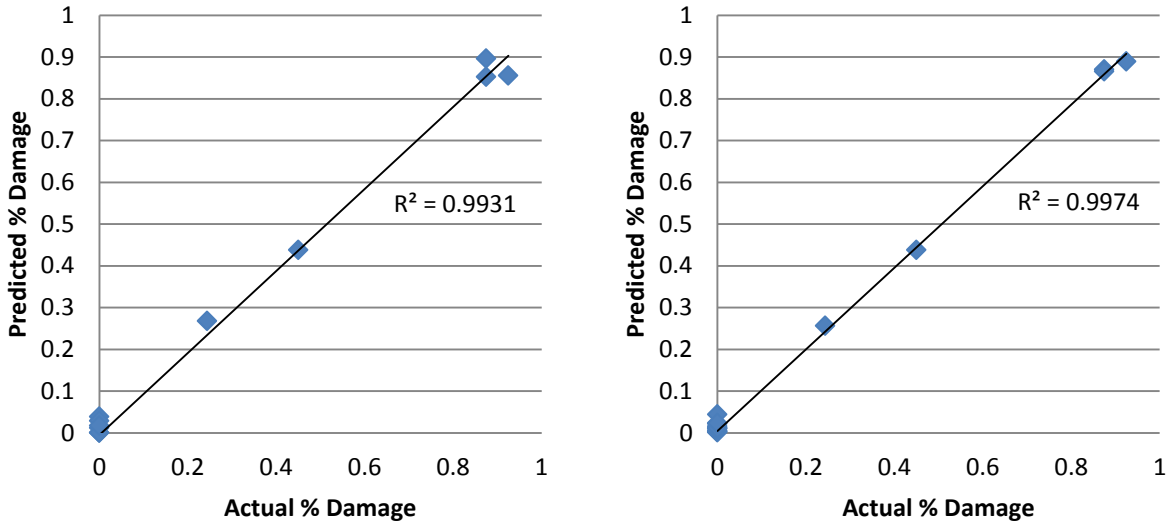

Figure 3-83. Damage Prediction Using PLS 'Red La Soda' Brown Rot Reflectance (left), 1st Derivative (right)

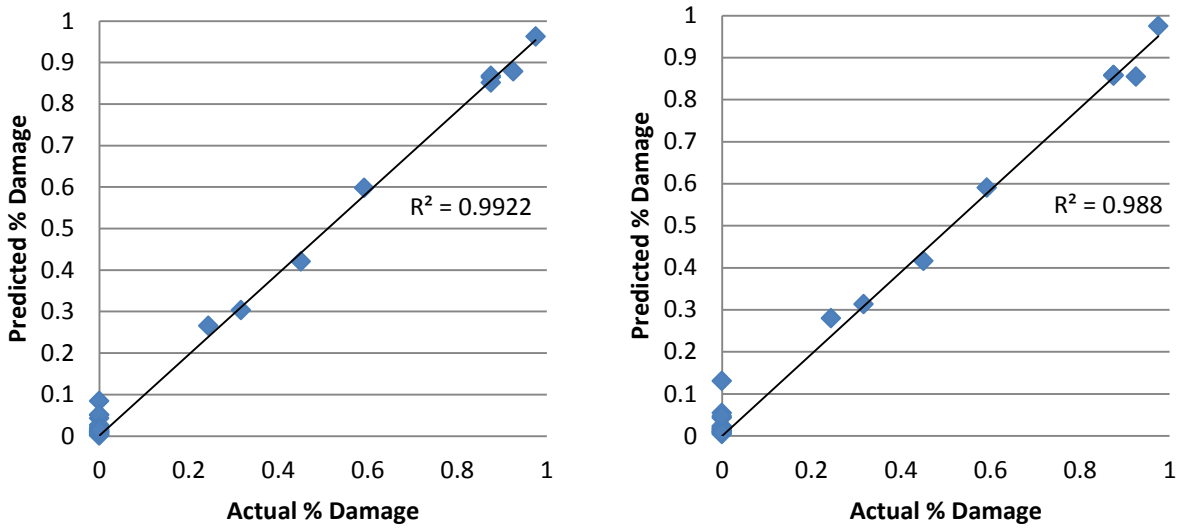

Figure 3-84. Damage Prediction Using PLS Combined Brown Rot Reflectance (left), 1st Derivative (right)

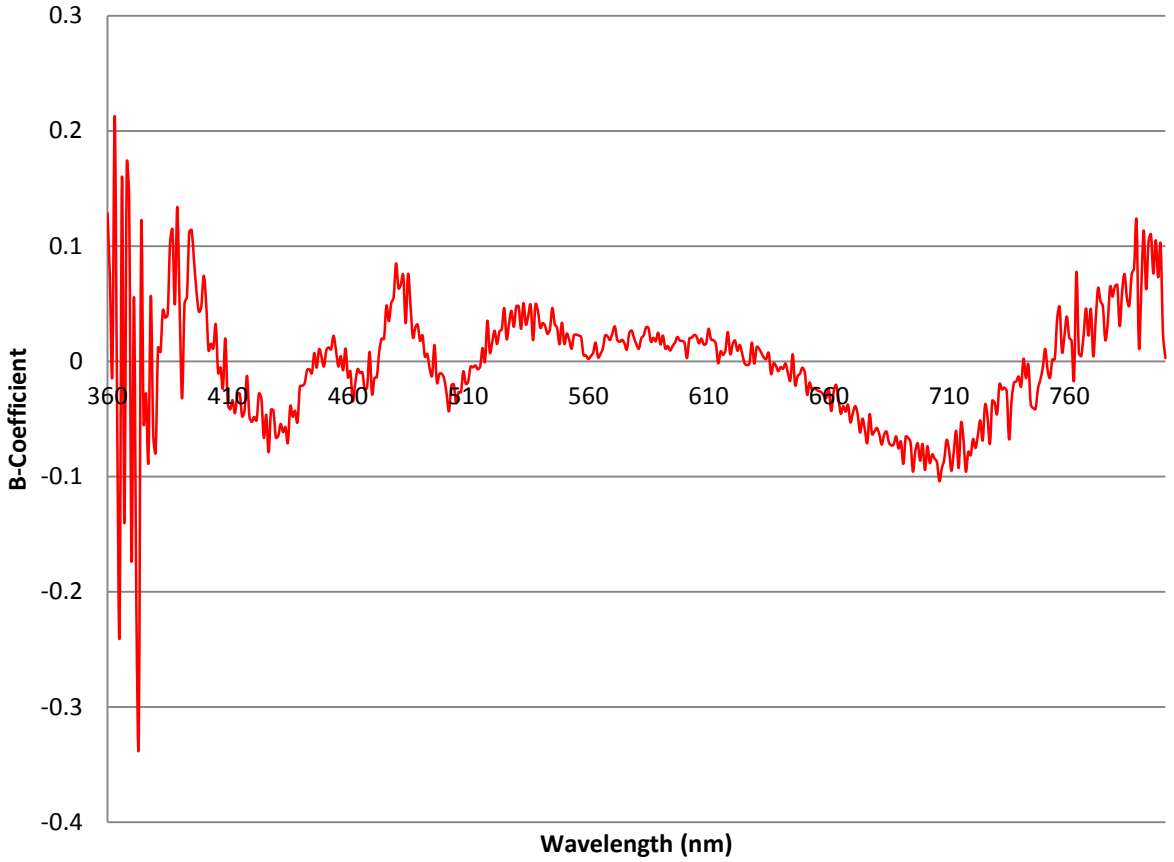

Figure 3-85. B-Coefficients 'Fabula' Brown Rot Reflectance

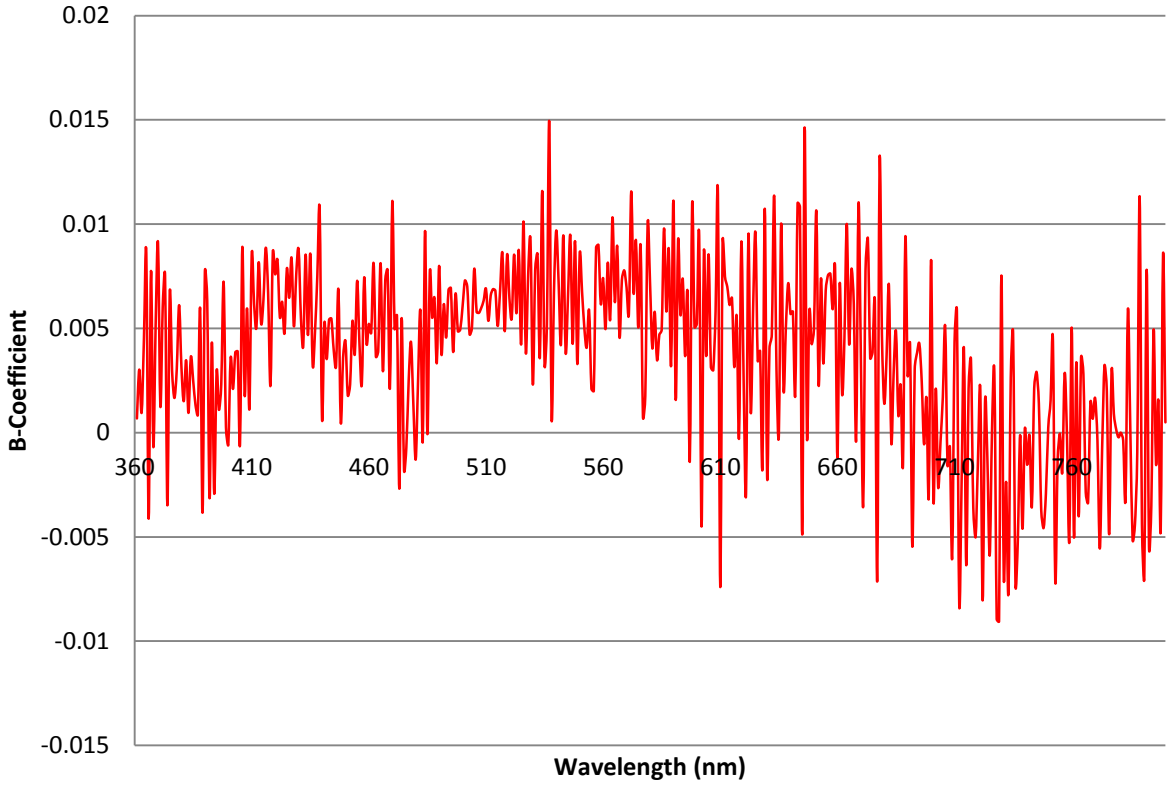

Figure 3-86. B-Coefficients 'Fabula' Brown Rot 1st Derivative Reflectance

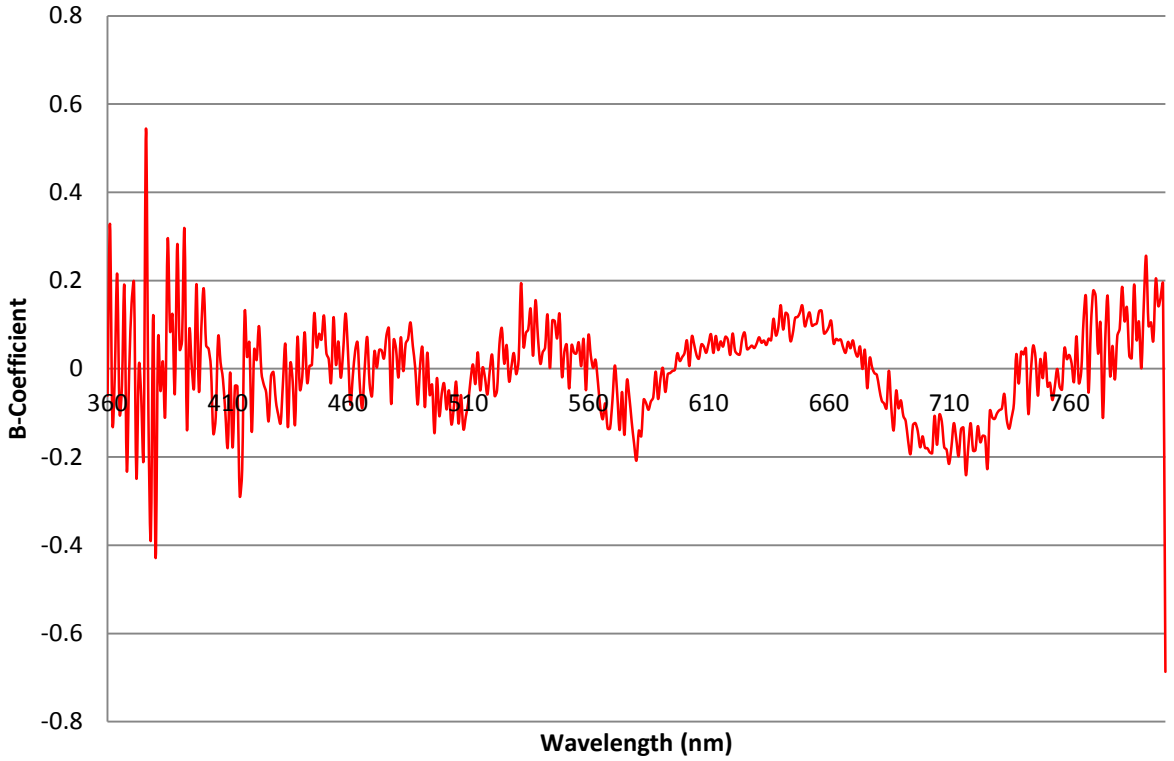

Figure 3-87. B-Coefficients 'Red La Soda' Brown Rot Reflectance

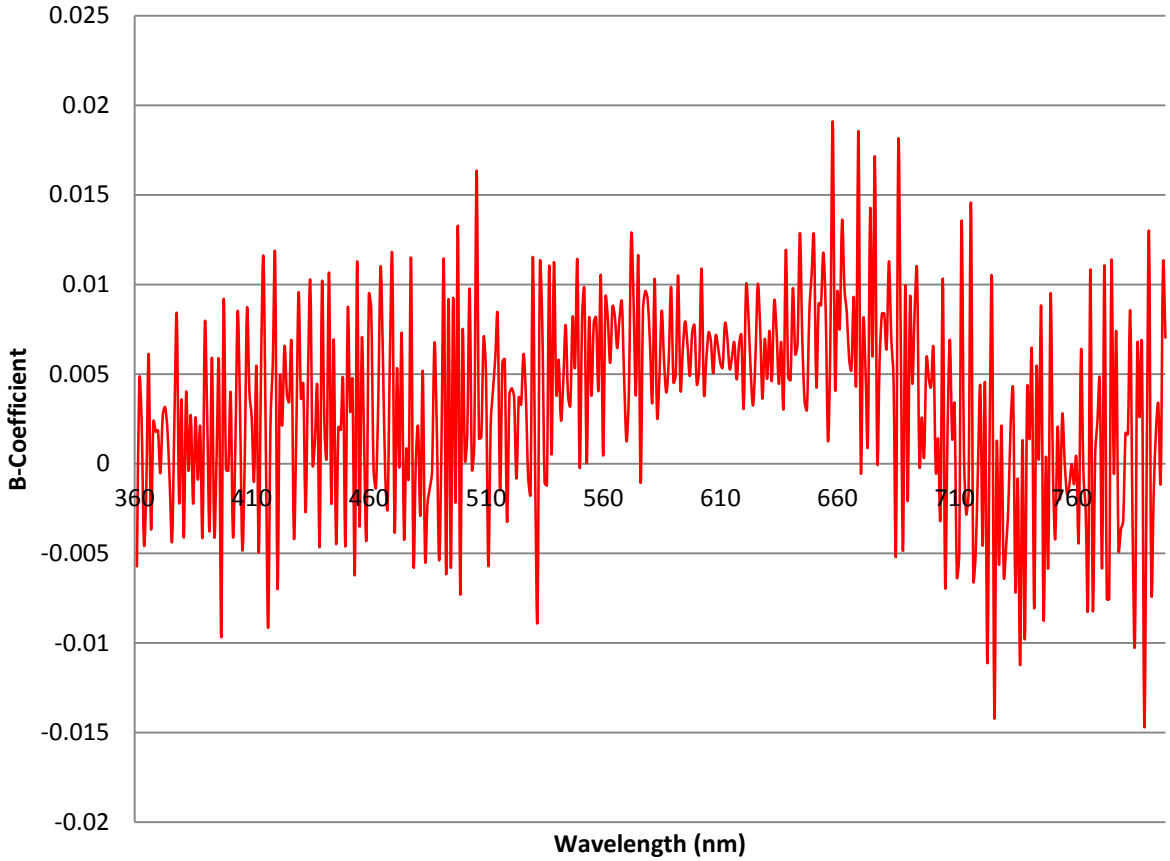

Figure 3-88. B-Coefficients 'Red La Soda' Brown Rot 1st Derivative Reflectance

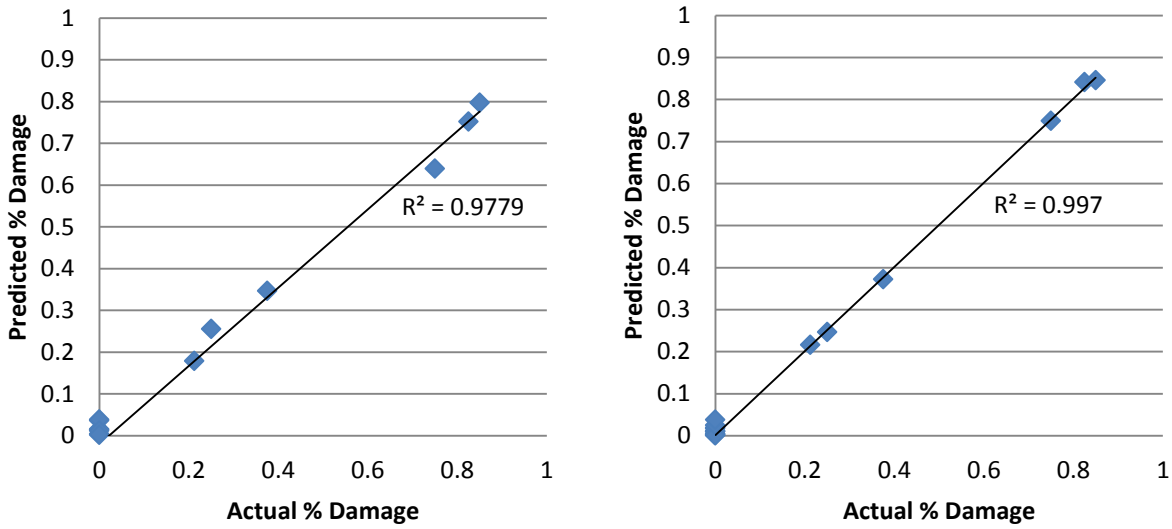

Figure 3-89. Damage Prediction Using PLS 'Fabula' Growth Cracking Reflectance (left), 1st Derivative (right)

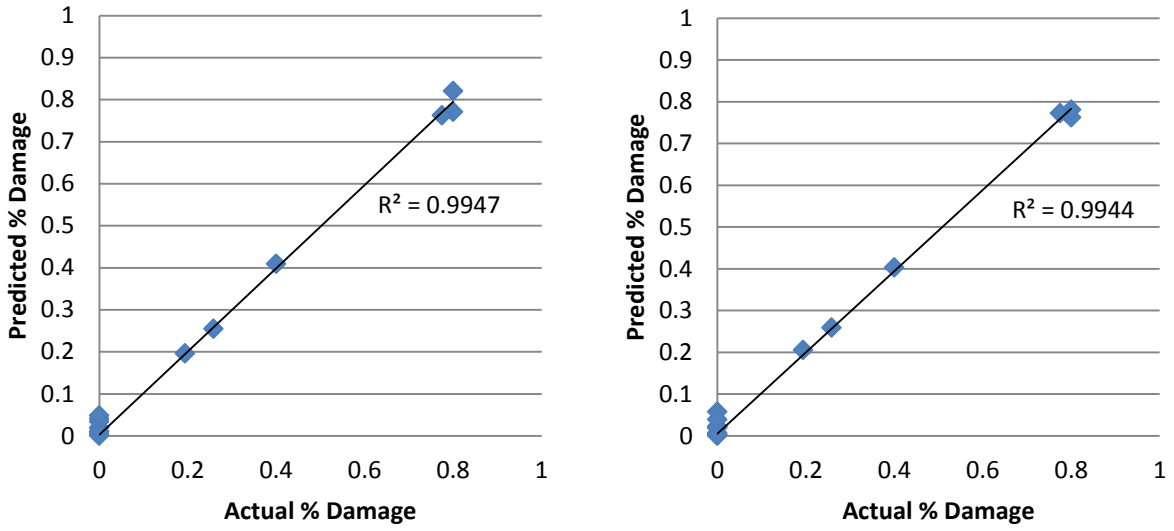

Figure 3-90. Damage Prediction Using PLS 'Red La Soda' Growth Cracking Reflectance (left), 1st Derivative (right)

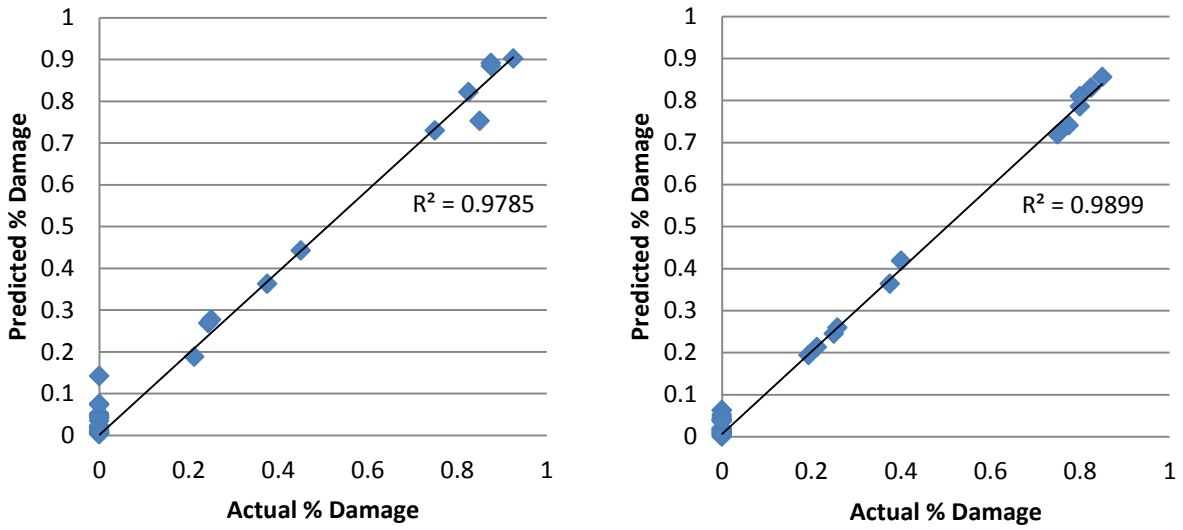

Figure 3-91. Damage Prediction Using PLS Combined Growth Cracking Reflectance (left), 1st Derivative (right)

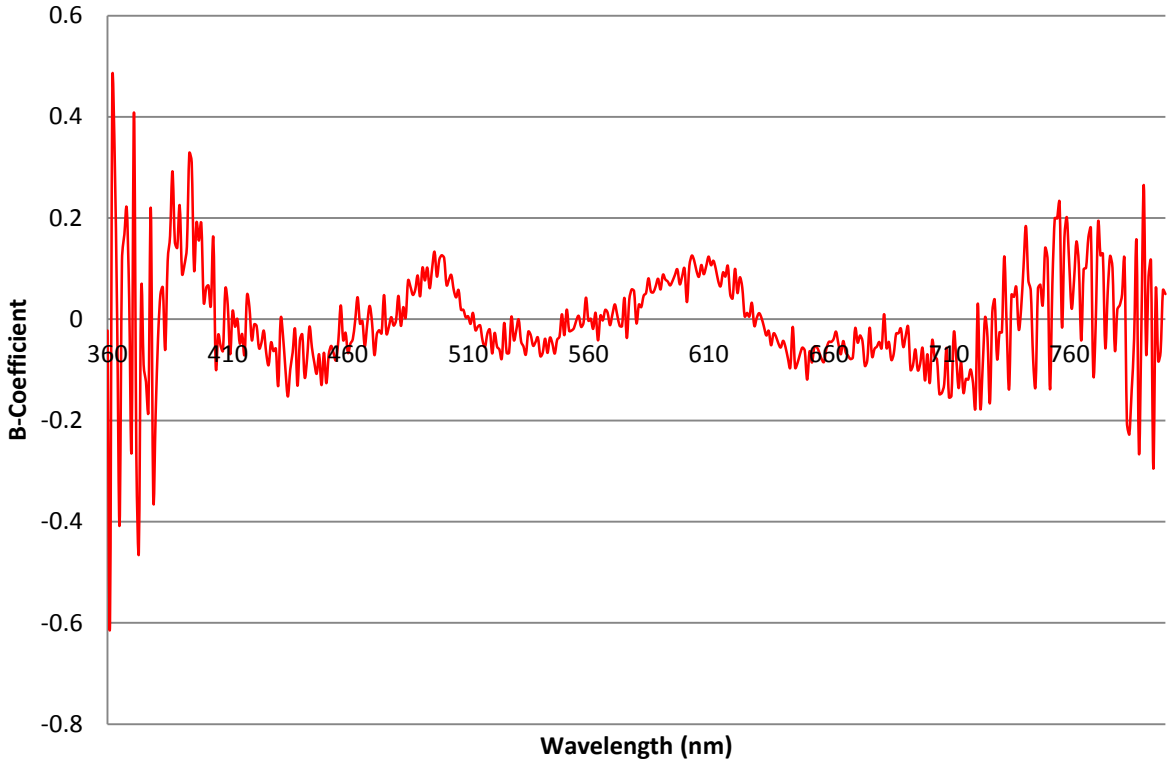

Figure 3-92. B-Coefficients 'Fabula' Growth Cracking Reflectance

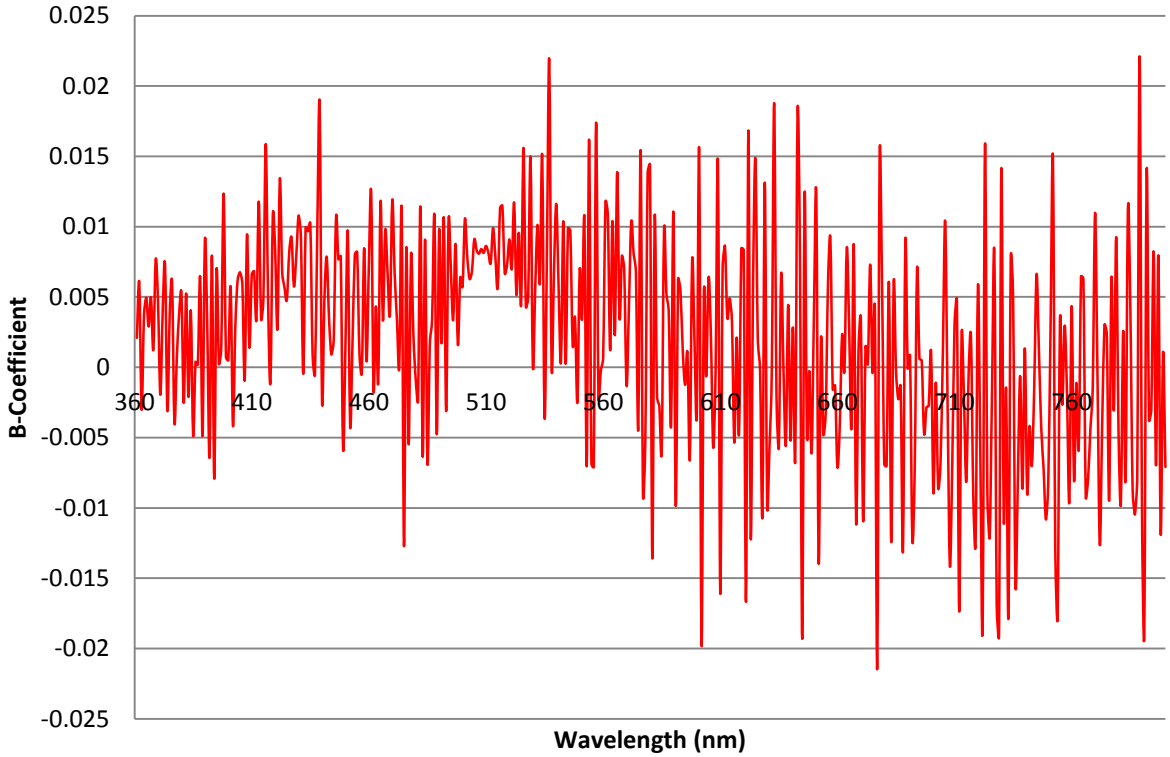

Figure 3-93. B-Coefficients 'Fabula' Growth Cracking 1st Derivative Reflectance

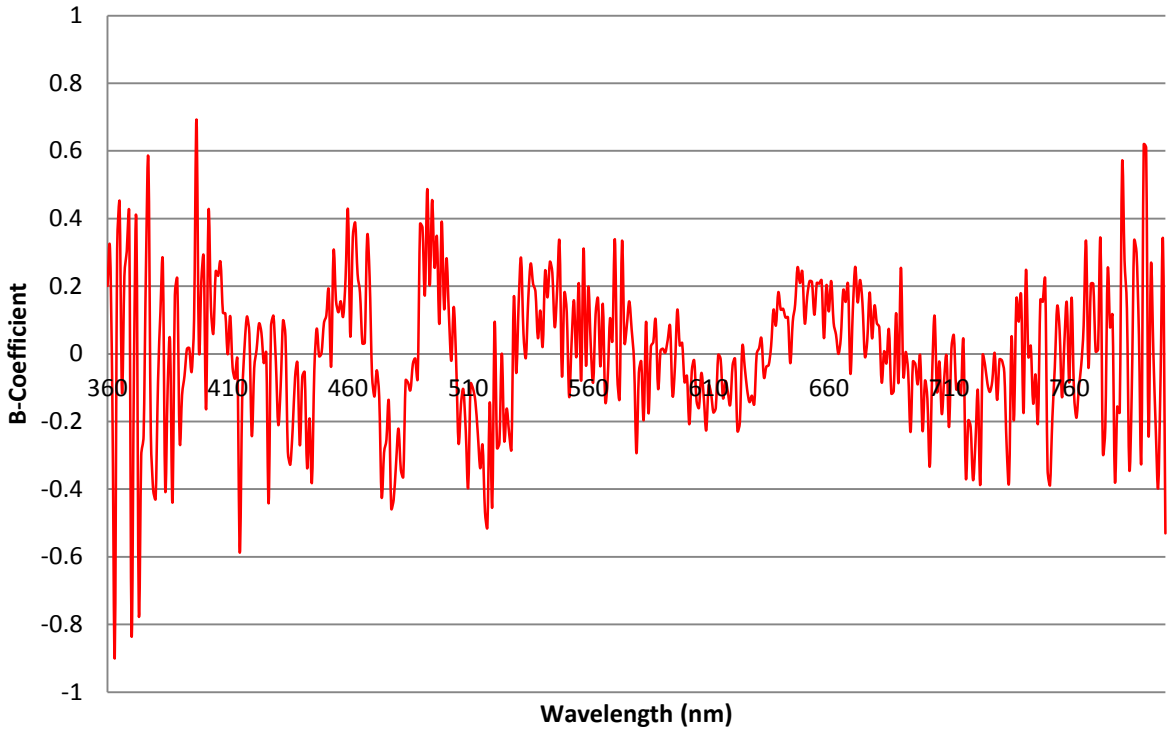

Figure 3-94. B-Coefficients 'Red La Soda' Growth Cracking Reflectance

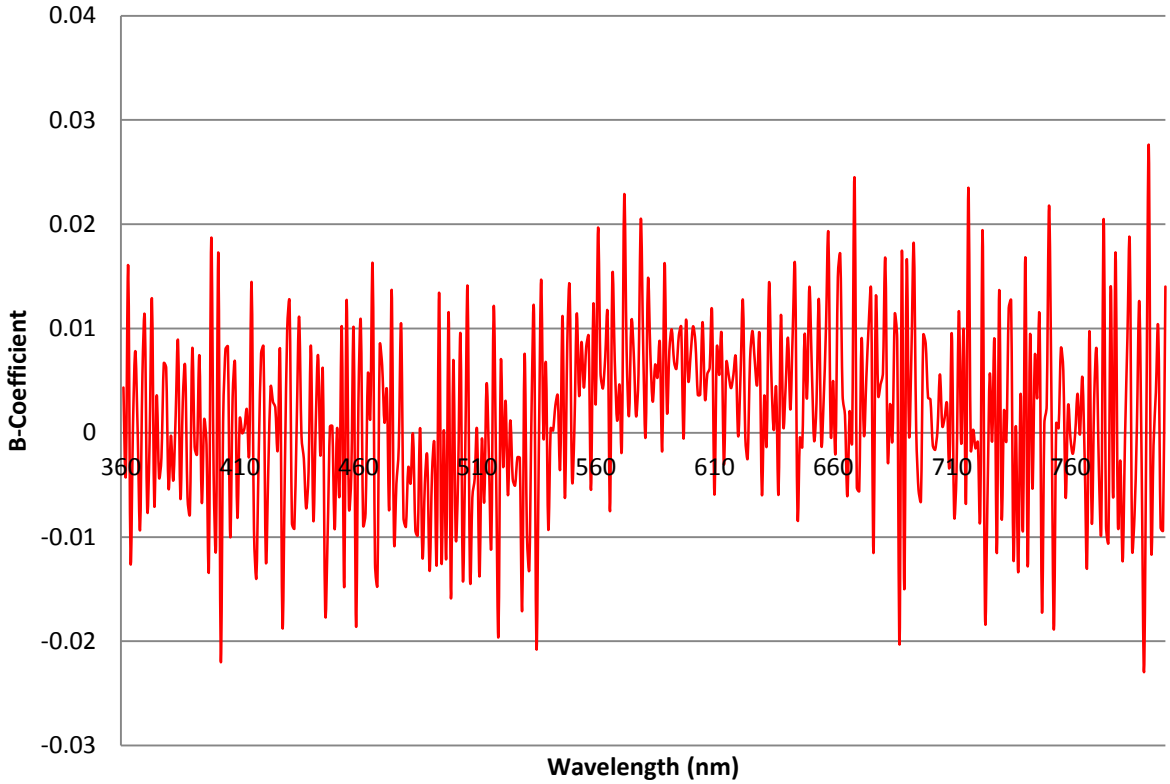

Figure 3-95. B-Coefficients 'Red La Soda' Growth Cracking 1st Derivative Reflectance

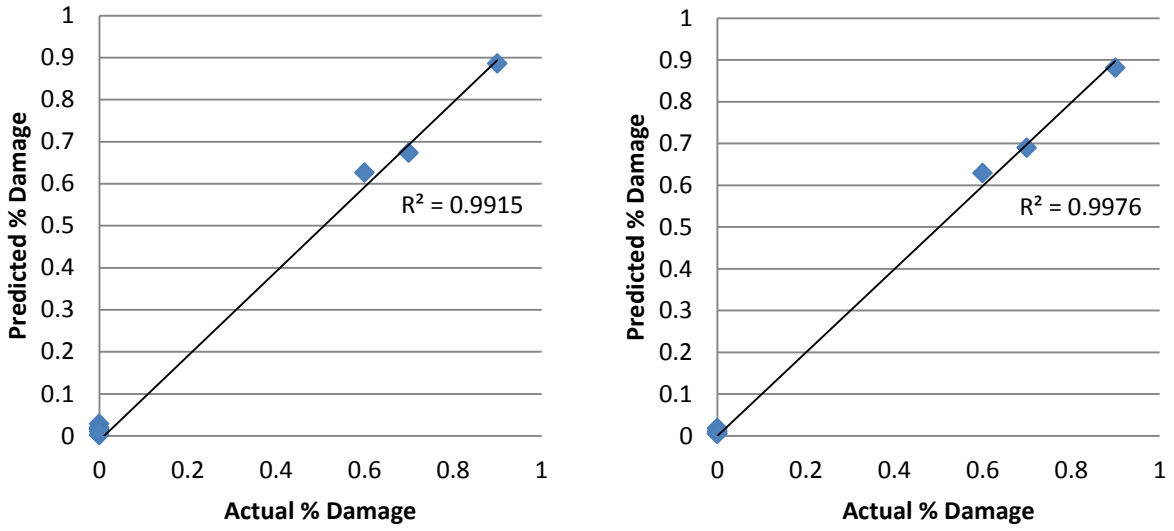

Figure 3-96. Damage Prediction Using PLS 'Red La Soda' Insect Damage Reflectance (left), 1st Derivative (right)

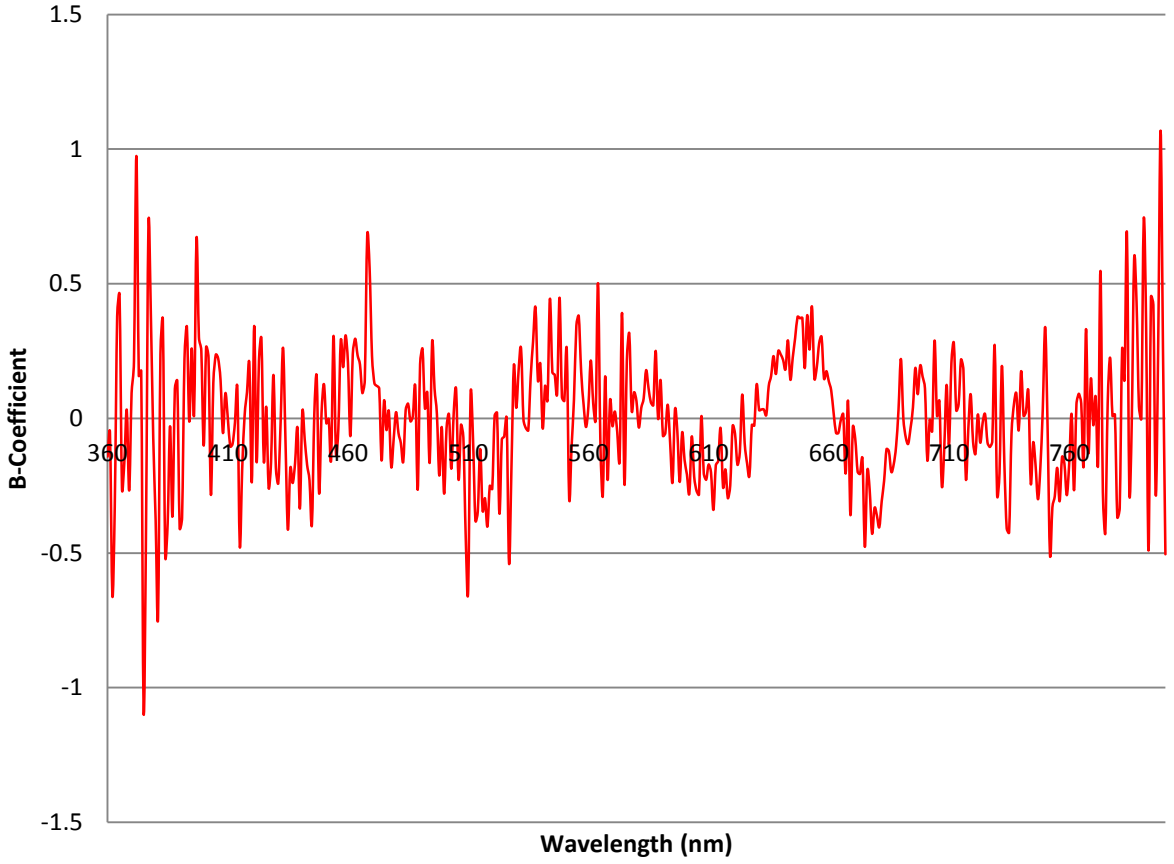

Figure 3-97. B-Coefficients 'Red La Soda' Insect Damage Reflectance

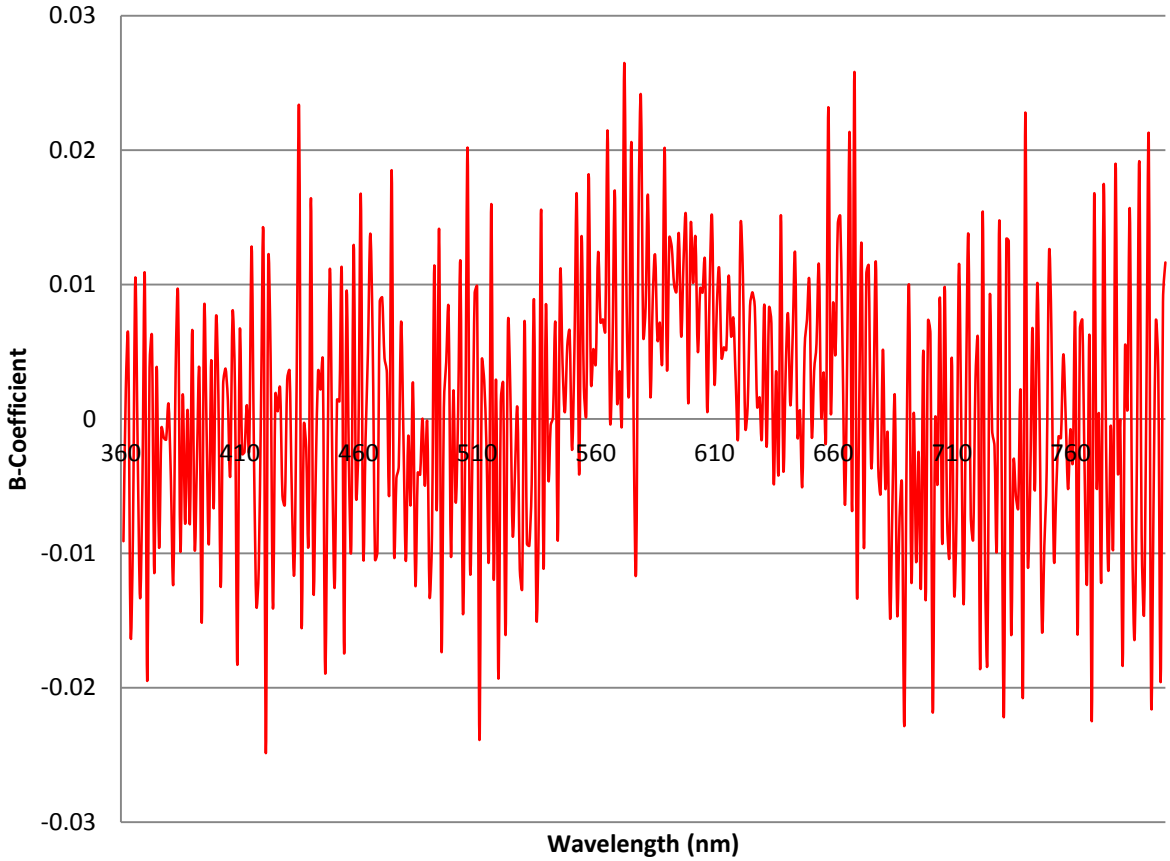

Figure 3-98. B-Coefficients 'Red La Soda' Insect Damage 1st Derivative Reflectance

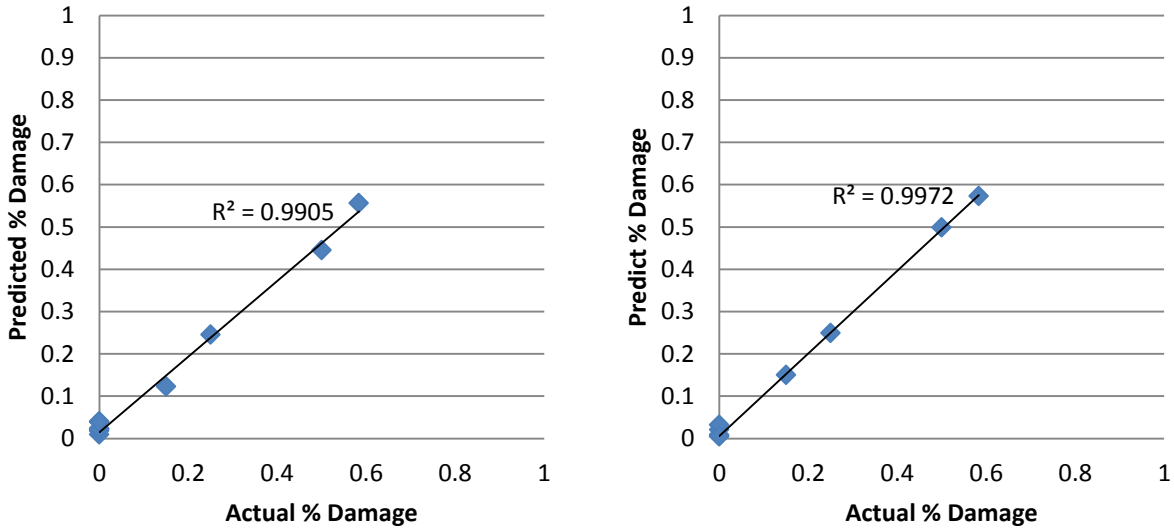

Figure 3-99. Damage Prediction Using SMLR 'Fabula' Internal Bruising Reflectance (left), 1st Derivative (right)

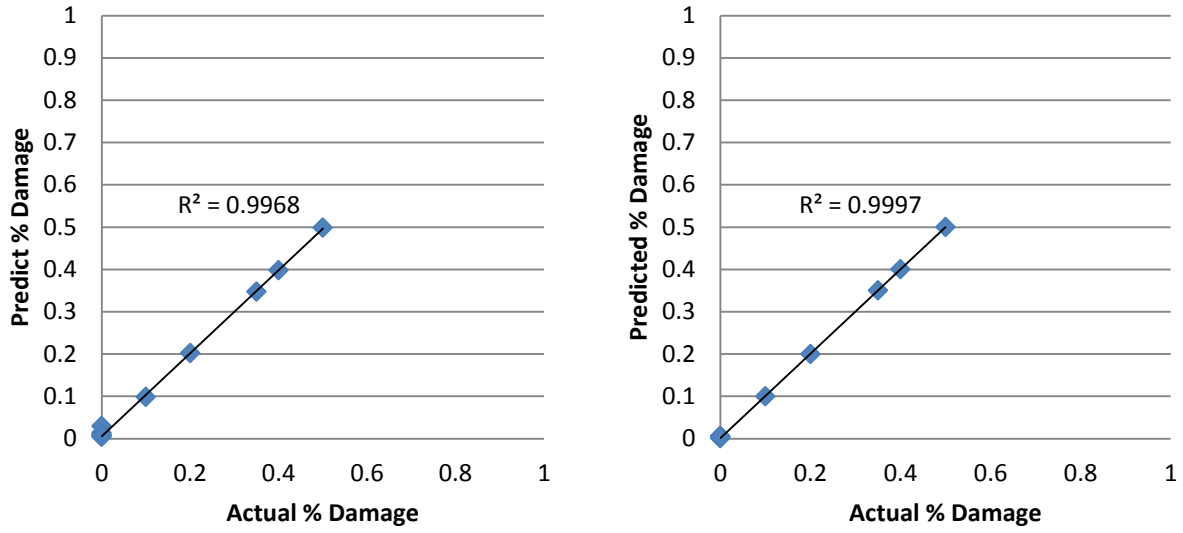

Figure 3-100. Damage Prediction Using SMLR 'Red La Soda' Internal Bruising Reflectance (left), 1st Derivative (right)

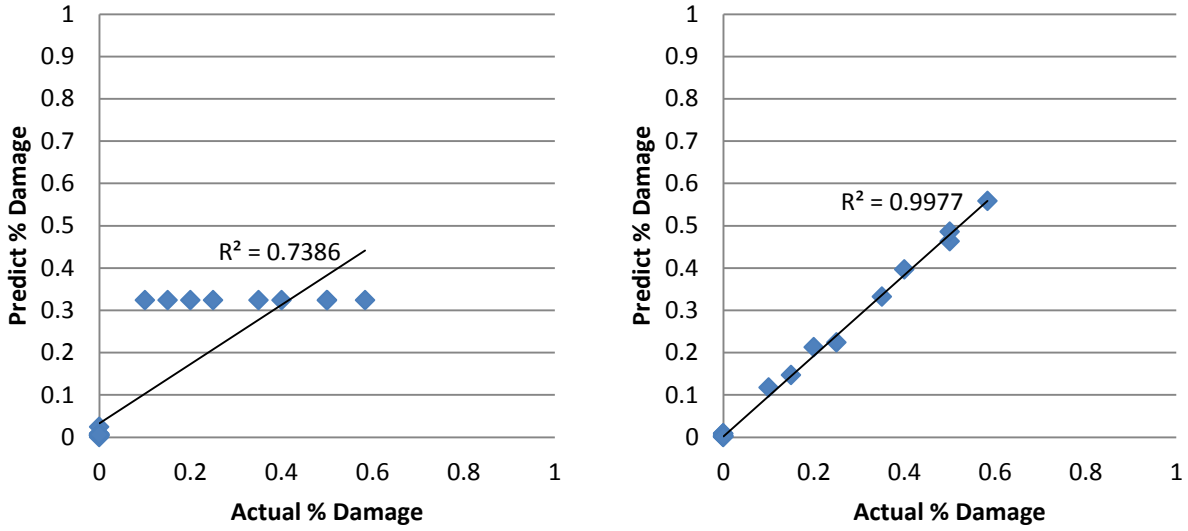

Figure 3-101. Damage Prediction Using SMLR Combined Internal Bruising Reflectance (left), 1st Derivative (right)

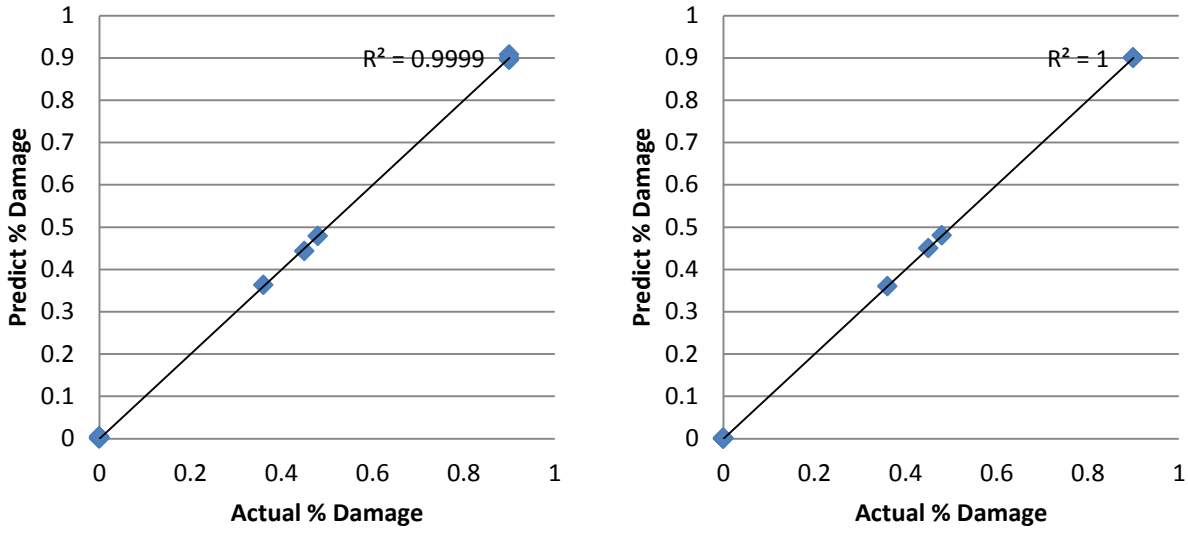

Figure 3-102. Damage Prediction Using SMLR 'Fabula' Shatter Reflectance (left), 1st Derivative (right)

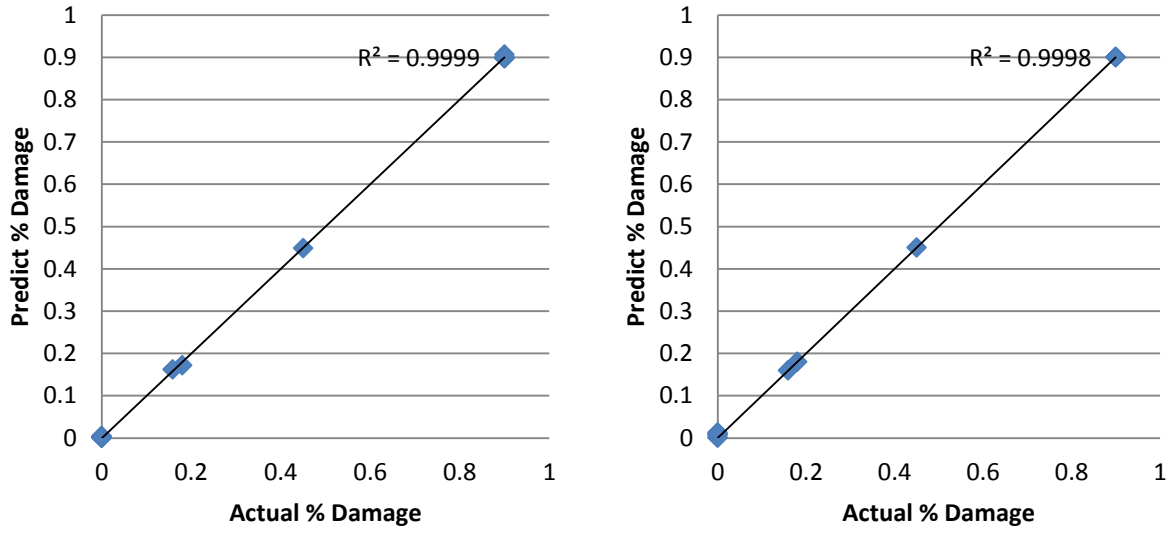

Figure 3-103. Damage Prediction Using SMLR 'Red La Soda' Shatter Reflectance (left), 1st Derivative (right)

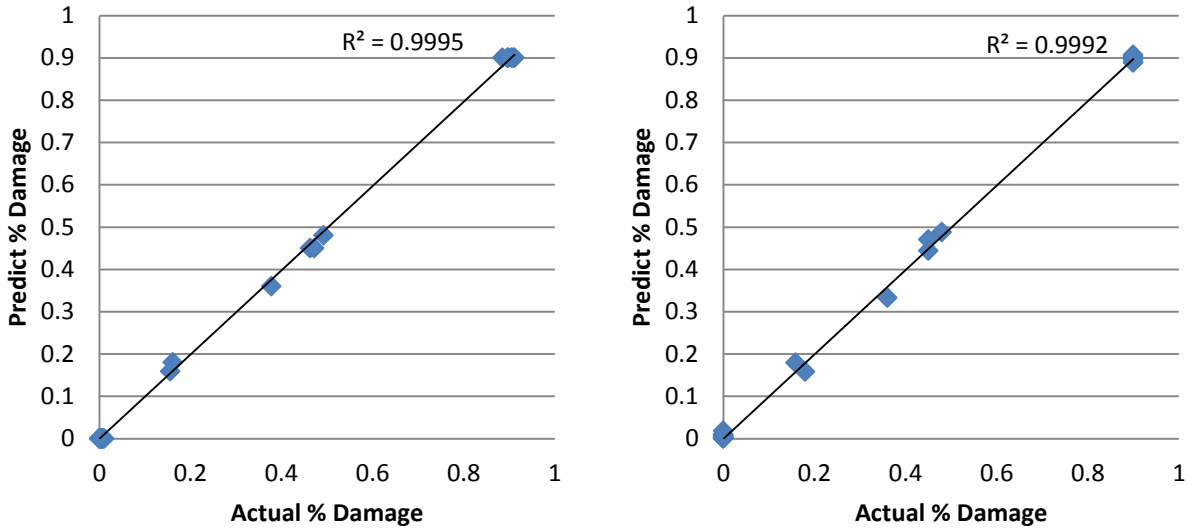

Figure 3-104. Damage Prediction Using SMLR Combined Shatter Reflectance (left), 1st Derivative (right)

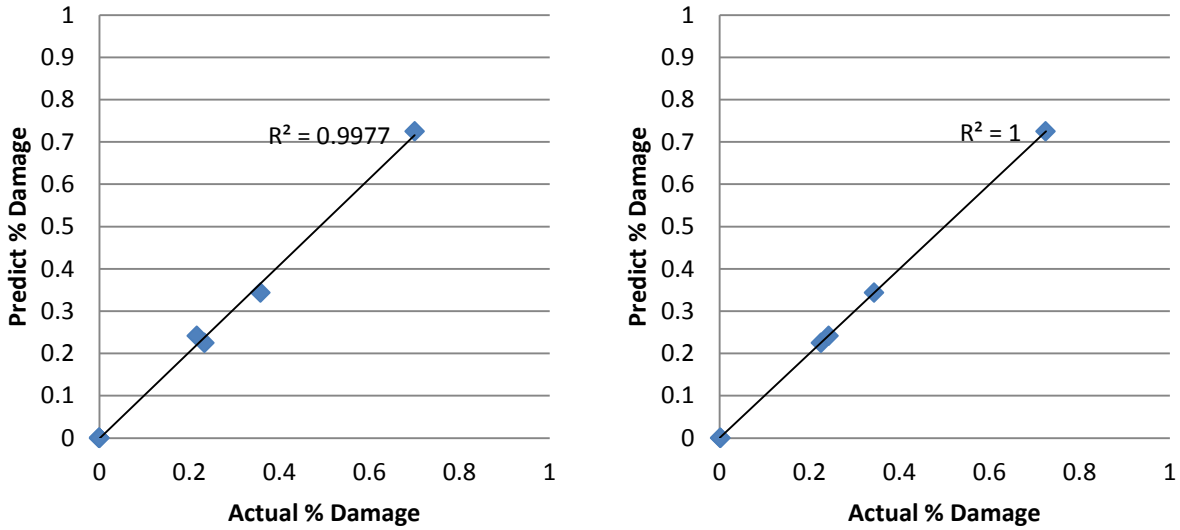

Figure 3-105. Damage Prediction Using SMLR 'Fabula' Greening Reflectance (left), 1st Derivative (right)

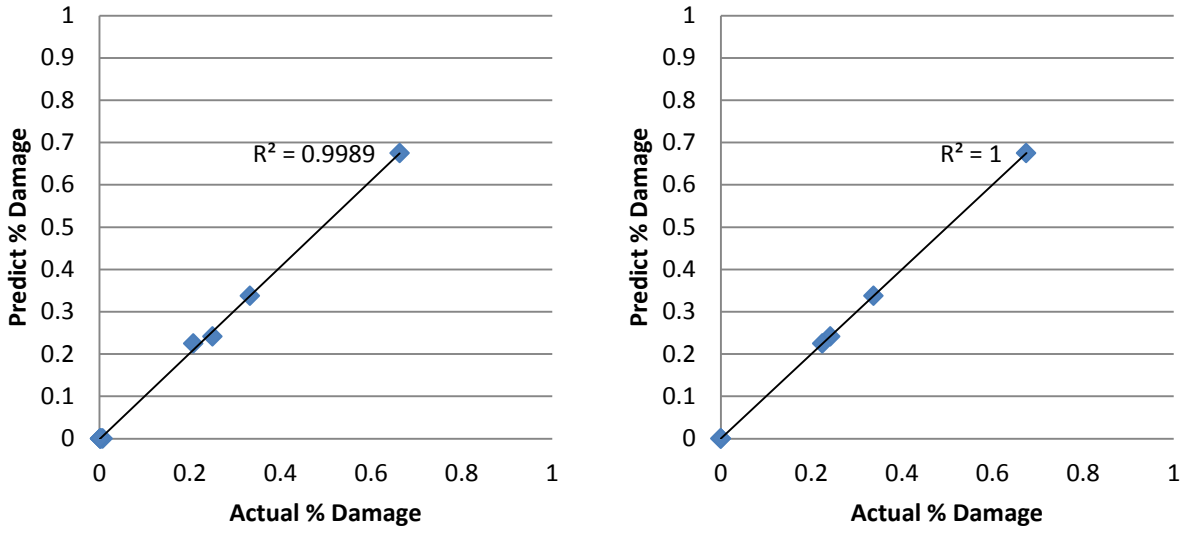

Figure 3-106. Damage Prediction Using SMLR 'Red La Soda' Greening Reflectance (left), 1st Derivative (right)

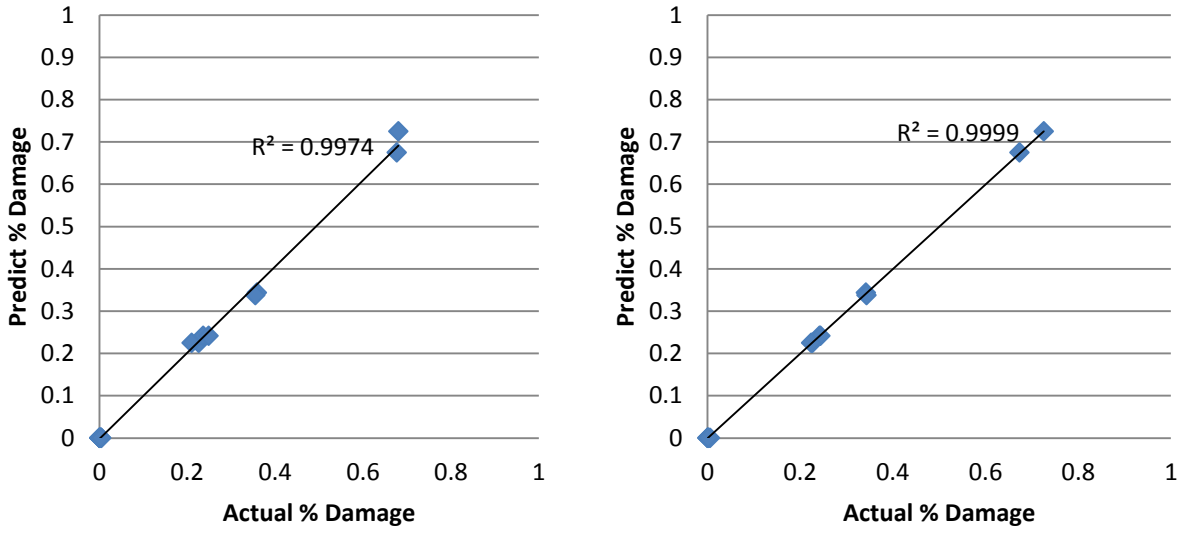

Figure 3-107. Damage Prediction Using SMLR Combined Greening Reflectance (left), 1st Derivative (right)

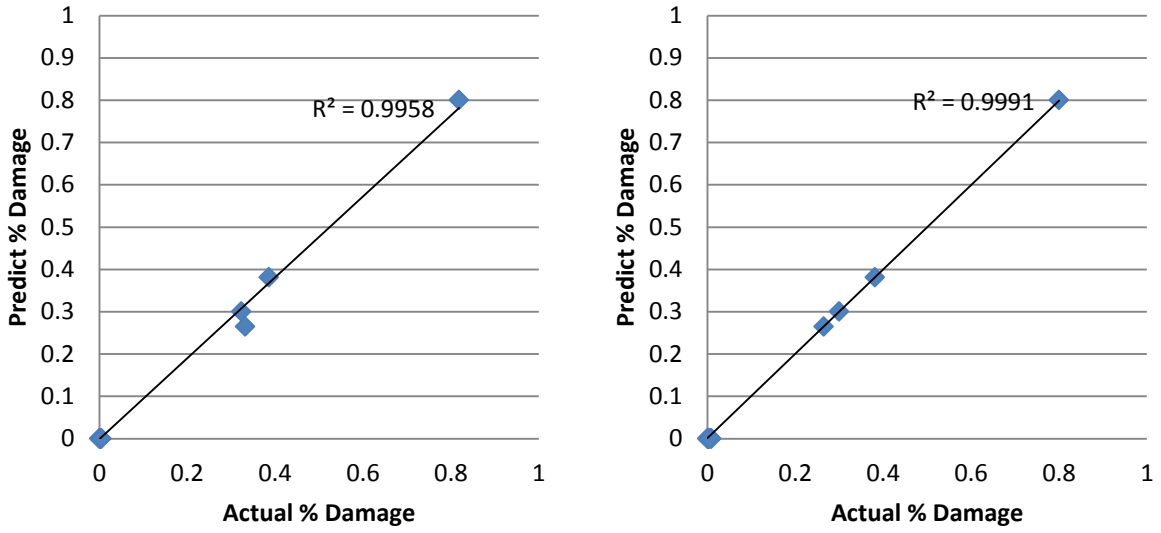

Figure 3-108. Damage Prediction Using SMLR 'Fabula' Sunscald Reflectance (left), 1st Derivative (right)

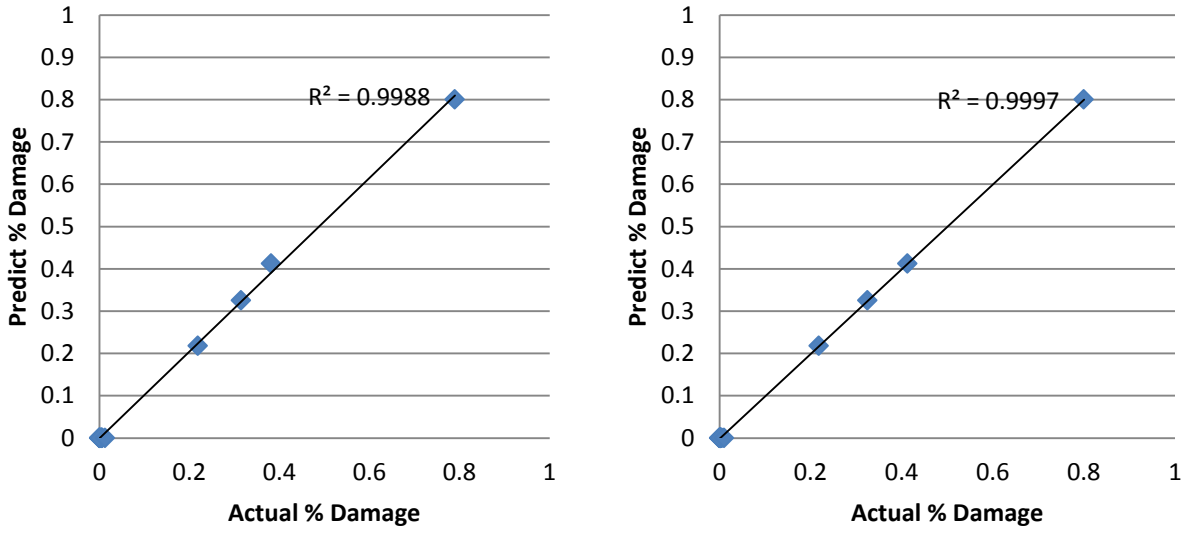

Figure 3-109. Damage Prediction Using SMLR 'Red La Soda' Sunscald Reflectance (left), 1st Derivative (right)

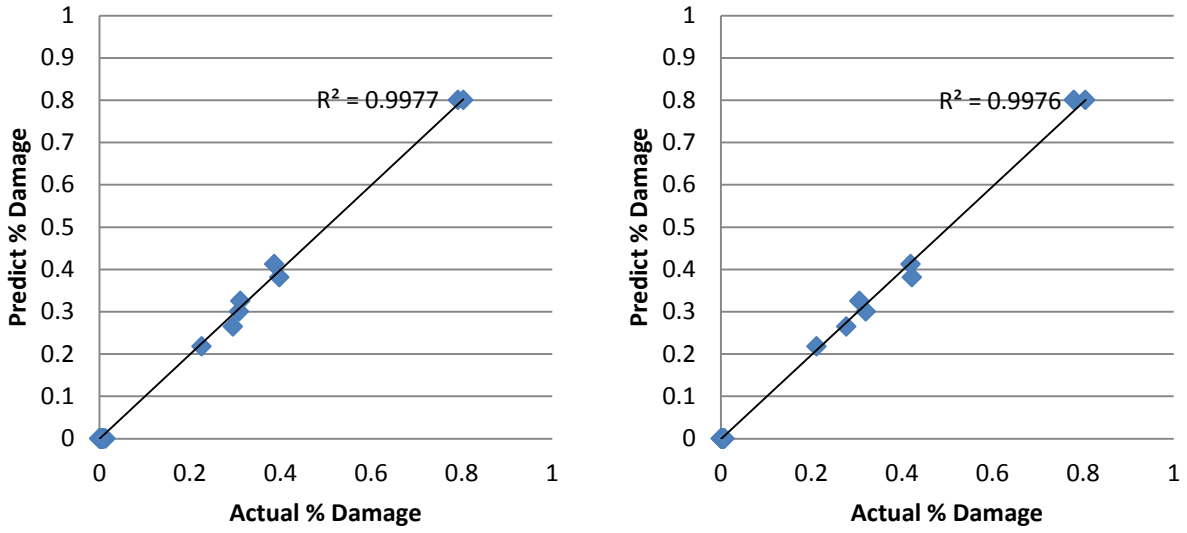

Figure 3-110. Damage Prediction Using SMLR Combined Sunscald Reflectance (left), 1st Derivative (right)

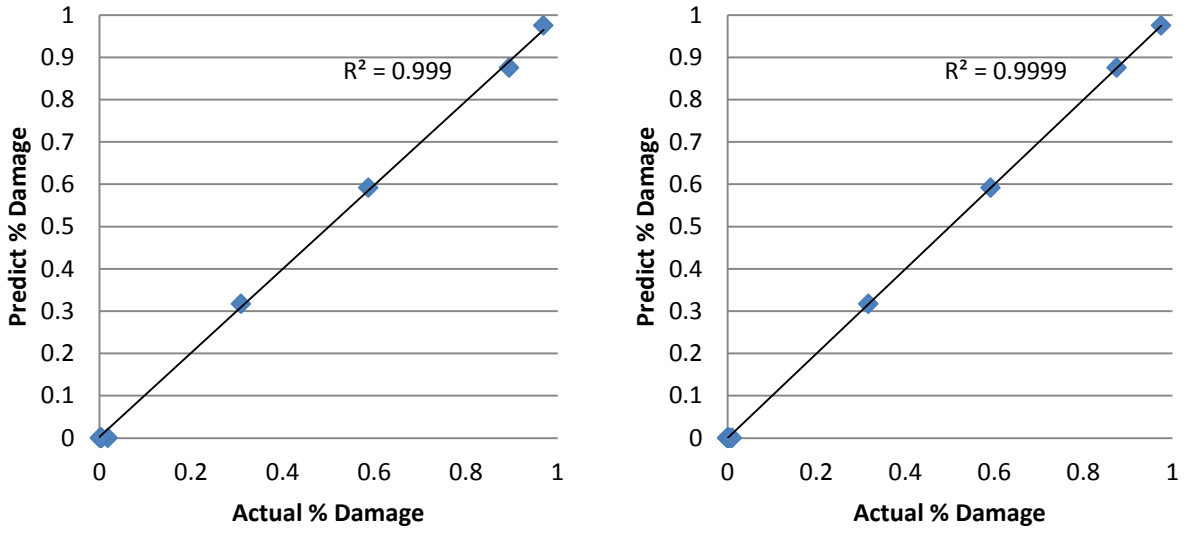

Figure 3-111. Damage Prediction Using SMLR 'Fabula' Brown Rot Reflectance (left), 1st Derivative (right)

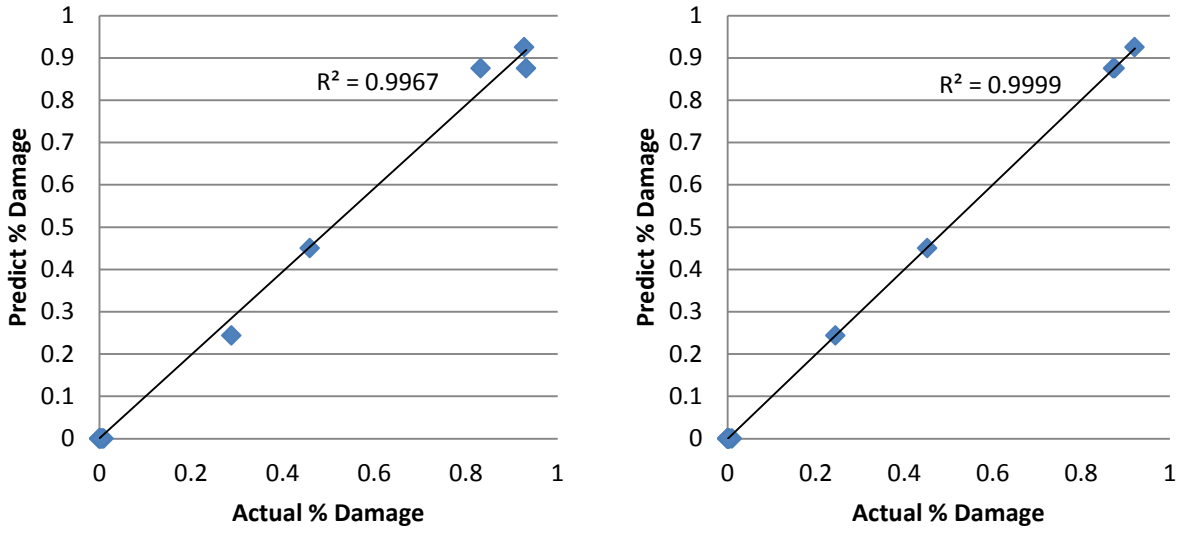

Figure 3-112. Damage Prediction Using SMLR 'Red La Soda' Brown Rot Reflectance (left), 1st Derivative (right)

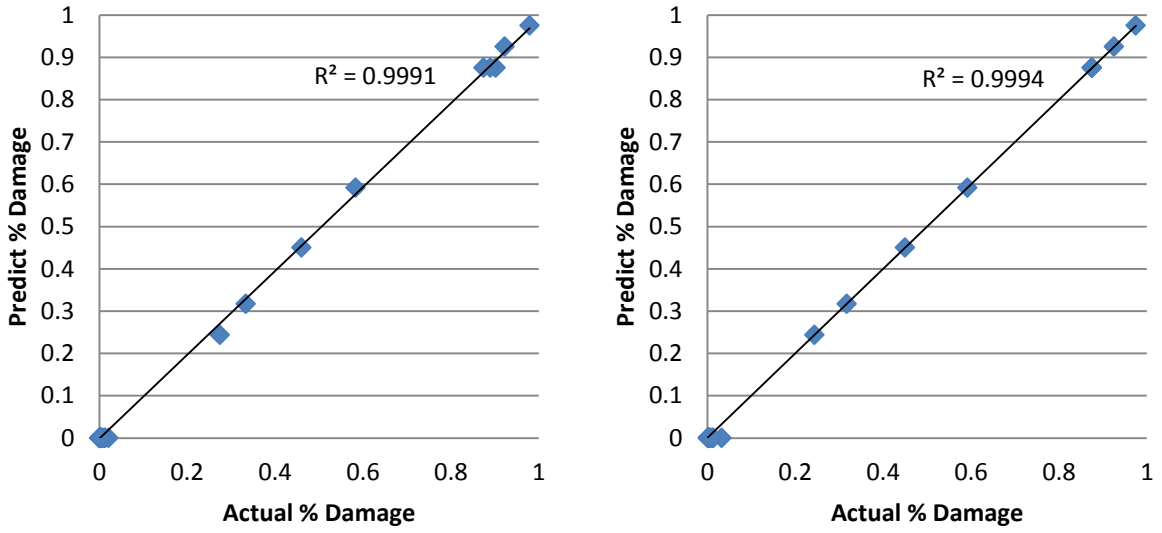

Figure 3-113. Damage Prediction Using SMLR Combined Brown Rot Reflectance (left), 1st Derivative (right)

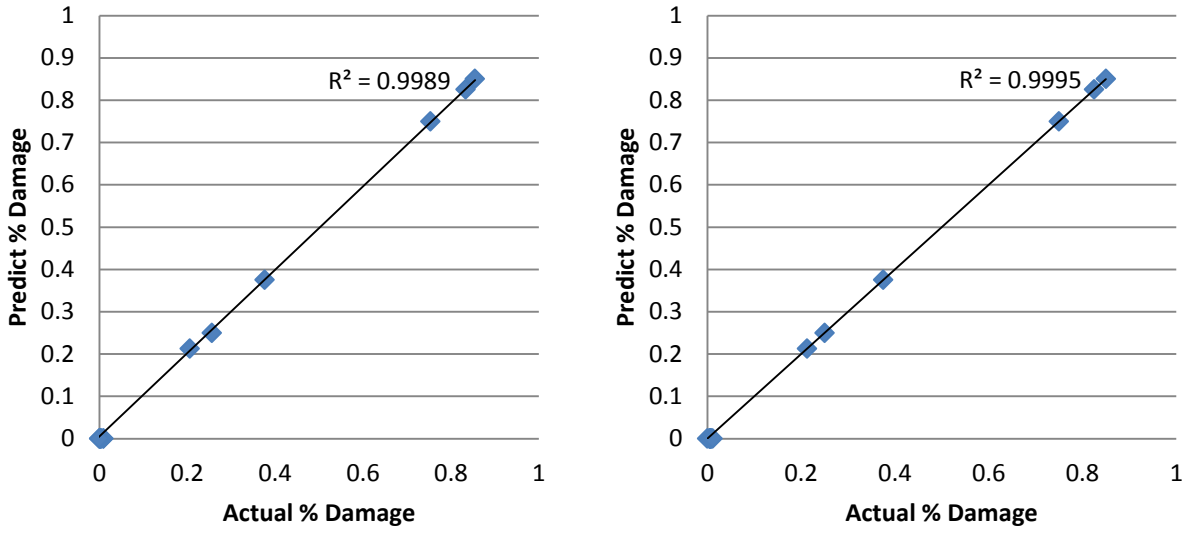

Figure 3-114. Damage Prediction Using SMLR 'Fabula' Cracking Reflectance (left), 1st Derivative (right)

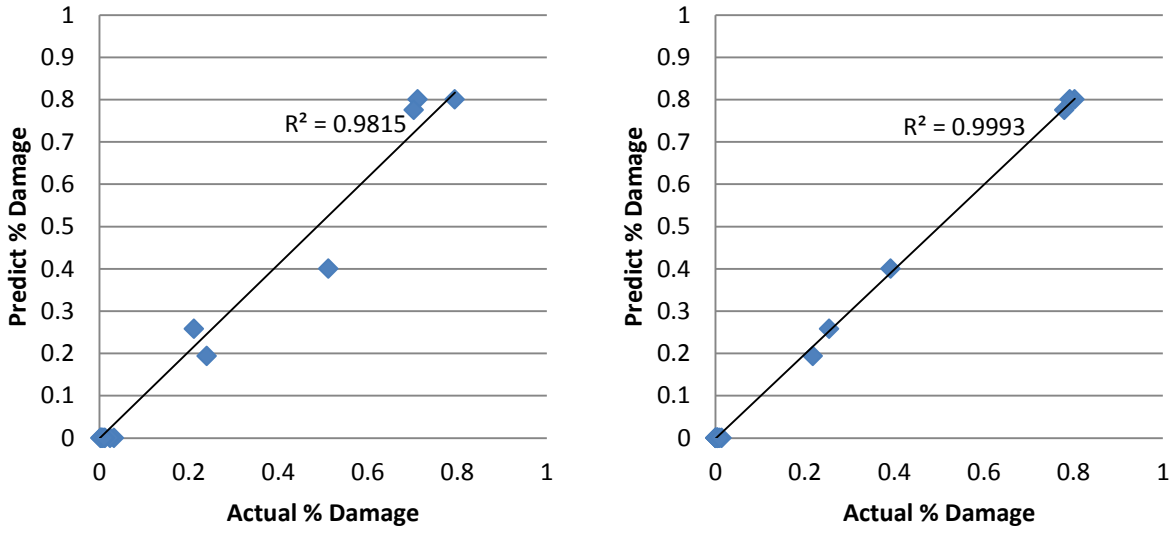

Figure 3-115. Damage Prediction Using SMLR 'Red La Soda' Cracking Reflectance (left), 1st Derivative (right)

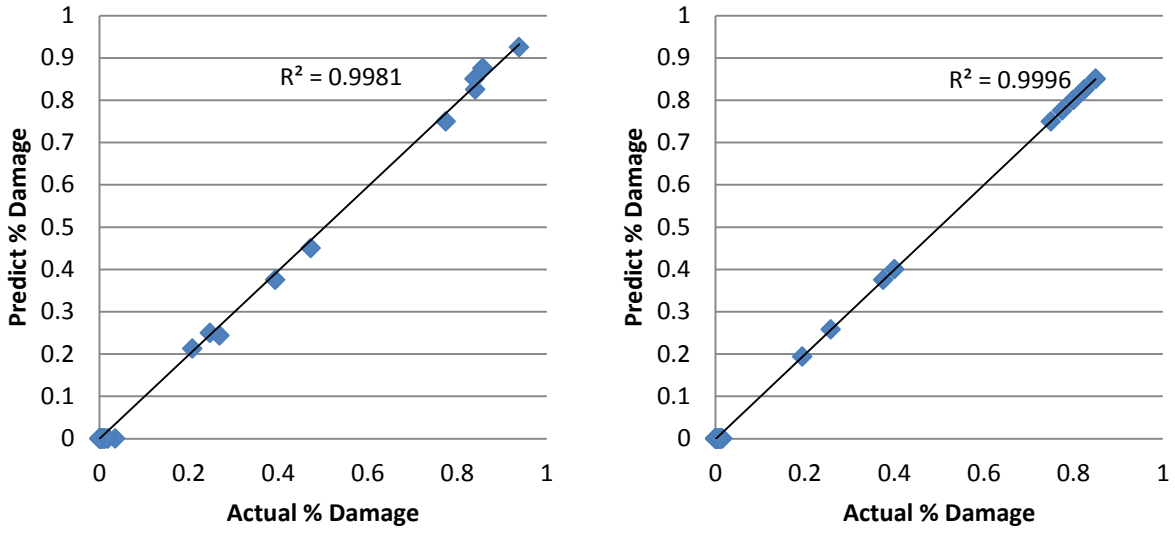

Figure 3-116. Damage Prediction Using SMLR Combined Cracking Reflectance (left), 1st Derivative (right)

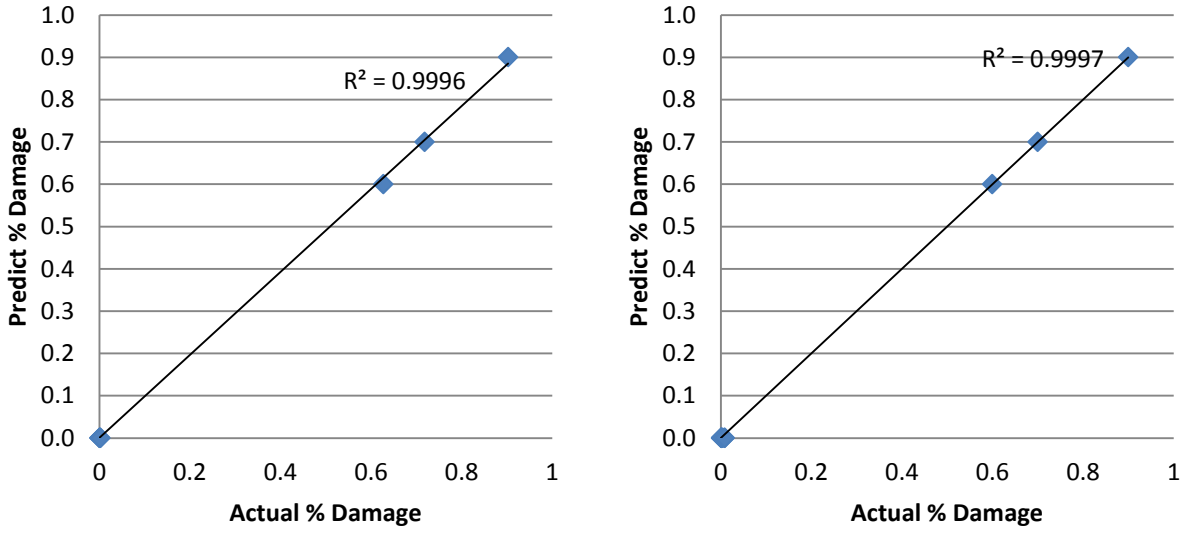

Figure 3-117. Damage Prediction Using SMLR 'Red La Soda' Insect Damage Reflectance (left), 1st Derivative (right)

Table 3-5. Results of ‘fabula’ SMLR analysis of sample sets

Disorder	Step	Variable entered	Partial R-square	Model R-square	F value	Pr > F
Internal bruising	1	w795	0.534	0.534	13.7	0.003
	2	w791	0.296	0.830	19.2	0.0011
	3	w435	0.090	0.920	11.3	0.0072
I.b. 1st der.	1	w408	0.675	0.675	24.9	0.0003
	2	w742	0.186	0.861	14.8	0.0027
	3	w531	0.095	0.956	21.5	0.0009
	4	w456	0.027	0.983	14.9	0.0039
	5	w482	0.012	0.995	21.0	0.0018
	6	w435	0.003	0.999	15.2	0.0059
Shatter	1	w432	0.030	0.951	11.3	0.0033
	2	w438	0.029	0.980	25.6	<.0001
	3	w383	0.008	0.988	11.2	0.0038
	4	w379	0.007	0.992	15.4	0.0011
	5	w382	0.004	0.996	15.9	0.0011
	6	w386	0.002	0.998	13.9	0.002
	7	w376	0.001	0.999	15.7	0.0014
	8	w471	0.001	1.000	15.6	0.0017
Shatter 1st der.	1	w499	0.942	0.942	324.0	<.0001
	2	w500	0.036	0.978	31.0	<.0001
	3	w629	0.009	0.987	12.2	0.0026
	4	w504	0.005	0.992	10.0	0.0056
	5	w688	0.004	0.996	14.0	0.0018
	6	w613	0.002	0.997	10.7	0.0051
	7	w722	0.001	0.998	7.7	0.0149
	8	w790	0.001	0.999	8.2	0.0134
	9	w690	0.001	1.000	12.2	0.0045
	10	w648	0.000	1.000	54.5	<.0001
	11	w654	0.000	1.000	9.3	0.0121
Greening	1	w702	0.986	0.986	775.6	<.0001
	2	w503	0.007	0.993	10.6	0.0087
Greening 1st der.	1	w688	0.990	0.990	1056.0	<.0001
	2	w510	0.010	0.999	143.6	<.0001
	3	w533	0.001	1.000	67.4	<.0001
	4	w625	0.000	1.000	18.1	0.0028
Sunscald	1	w446	0.954	0.954	247.4	<.0001
	2	w432	0.025	0.979	13.3	0.0039
Sunscald 1st der.	1	w512	0.928	0.928	154.2	<.0001
	2	w610	0.056	0.984	38.1	<.0001
	3	w474	0.008	0.992	9.1	0.0129
	4	w737	0.006	0.998	23.2	0.0009

Table 3-5. Continued

Disorder	Step	Variable entered	Partial R-square	Model R-square	F value	Pr > F
	5	w449	0.002	0.999	16.8	0.0034
	6	w417	0.000	1.000	5.8	0.0467
	7	w711	0.000	1.000	30.3	0.0015
	8	w611	0.000	1.000	30.7	0.0026
Brown rot	1	w689	0.994	0.994	1950.4	<.0001
	2	w688	0.003	0.997	8.3	0.0163
Brown rot 1st der.	1	w518	0.976	0.976	453.6	<.0001
	2	w792	0.014	0.990	13.8	0.004
	3	w625	0.006	0.996	15.1	0.0037
	4	w421	0.002	0.999	13.8	0.006
	5	w650	0.001	1.000	23.8	0.0018
	6	w543	0.000	1.000	63.3	0.0002
Growth cracking	1	w545	0.949	0.949	221.0	<.0001
	2	w516	0.034	0.983	21.9	0.0007
	3	w517	0.007	0.990	7.2	0.0232
	4	w547	0.005	0.995	8.5	0.017
	5	w477	0.003	0.997	7.3	0.0273
	6	w543	0.002	0.999	8.5	0.0226
	7	w486	0.001	1.000	8.7	0.0256
Growth cracking 1st der.	1	w510	0.965	0.965	330.9	<.0001
	2	w769	0.020	0.985	15.2	0.0025
	3	w528	0.010	0.995	21.3	0.001
	4	w453	0.003	0.998	15.2	0.0036
	5	w529	0.001	0.999	6.7	0.032
	6	w473	0.001	1.000	8.6	0.0221

Table 3-6. Results of ‘red la soda’ SMLR analysis of sample sets

Disorder	Step	Variable entered	Partial R-square	Model R-square	F value	Pr > F
Internal bruising	1	w774	0.137	0.904	17.2	0.001
	2	w776	0.030	0.935	5.1	0.045
	3	w763	0.034	0.944	6.6	0.026
	4	w788	0.022	0.965	6.3	0.031
	5	w784	0.017	0.982	8.7	0.016
I.b. 1st der.	1	w640	0.716	0.716	32.7	<.0001
	2	w412	0.151	0.867	13.7	0.003
	3	w705	0.072	0.939	13.0	0.004
	4	w648	0.033	0.972	11.7	0.007
	5	w650	0.021	0.993	28.8	0.001
	6	w786	0.006	1.000	111.7	<.0001
	7	w681	0.000	1.000	14.8	0.006
	8	w484	0.000	1.000	13.3	0.011
Shatter	1	w568	0.996	0.996	4203.3	<.0001
	2	w398	0.001	1.000	38.6	<.0001
	3	w588	0.000	1.000	15.4	0.001
	4	w403	0.000	1.000	6.5	0.022
	5	w514	0.000	1.000	11.7	0.004
Shatter 1st der.	1	w502	0.985	0.985	1250.1	<.0001
	2	w625	0.010	0.995	37.6	<.0001
	3	w788	0.003	0.998	27.8	<.0001
	4	w576	0.001	0.999	11.0	0.004
	5	w585	0.000	0.999	9.3	0.008
	6	w471	0.000	1.000	9.5	0.008
	7	w642	0.000	1.000	8.9	0.011
	8	w621	0.000	1.000	11.8	0.005
	9	w479	0.000	1.000	12.5	0.005
Greening	1	w680	0.988	0.988	873.1	<.0001
	2	w675	0.010	0.998	46.8	<.0001
Greening 1st der.	1	w650	0.991	0.991	1173.4	<.0001
	2	w391	0.008	0.999	58.0	<.0001
	3	w673	0.001	1.000	24.9	0.001
	4	w730	0.000	1.000	31.8	0.001
Sunscald	1	w435	0.952	0.952	199.9	<.0001
	2	w433	0.033	0.985	20.0	0.002
Sunscald 1st der.	1	w750	0.034	0.990	31.0	0.000
	2	w608	0.005	0.995	8.0	0.022
	3	w425	0.003	0.998	10.7	0.014
	4	w530	0.002	0.999	16.2	0.005
	5	w444	0.001	1.000	37.9	0.001

Table 3-6. Continued

Disorder	Step	Variable entered	Partial R-square	Model R-square	F value	Pr > F
	6	w675	0.000	1.000	12.6	0.017
Brown rot	1	w665	0.974	0.974	477.5	<.0001
	2	w607	0.009	0.982	6.1	0.030
Brown rot 1st der.	1	w631	0.982	0.982	717.9	<.0001
	2	w781	0.011	0.993	17.8	0.001
	3	w776	0.004	0.997	12.0	0.005
	4	w629	0.002	0.998	11.3	0.007
	5	w442	0.001	0.999	6.6	0.030
	6	w615	0.001	1.000	8.9	0.018
Growth cracking	1	w381	0.879	0.879	87.4	<.0001
Growth cracking 1st der.	1	w622	0.955	0.955	254.1	<.0001
	2	w433	0.024	0.979	12.1	0.005
	3	w625	0.016	0.995	29.1	0.000
	4	w633	0.003	0.998	13.7	0.005
Insect damage	1	w800	0.889	0.889	24.1	0.016
Insect damage 1st der.	1	w549	0.981	0.981	150.8	0.001
	2	w586	0.020	1.000	3573.2	0.000

Table 3-7. Results of combined varieties SMLR analysis of sample sets

Disorder	Step	Variable entered	Partial R-square	Model R-square	F value	Pr > F
Internal bruising	No variable met the 0.0500 significance level for entry into the model.					
I.b. 1st der.	1	w682	0.359	0.359	15.1	0.001
	2	w667	0.180	0.539	10.1	0.004
	3	w716	0.247	0.786	28.9	<.0001
	4	w427	0.044	0.831	6.3	0.020
	5	w589	0.044	0.874	7.9	0.010
	6	w558	0.029	0.903	6.6	0.018
	7	w791	0.029	0.932	8.8	0.007
	8	w576	0.018	0.949	6.9	0.016
	9	w540	0.014	0.963	7.2	0.015
	10	w443	0.008	0.971	4.9	0.040
Shatter	1	w378	0.855	0.855	242.1	<.0001
	2	w362	0.021	0.978	36.9	<.0001
	3	w388	0.006	0.984	15.0	0.000
	4	w395	0.003	0.990	9.4	0.004
	5	w422	0.005	0.995	32.1	<.0001
Shatter 1st der.	1	w672	0.803	0.803	167.0	<.0001
	2	w388	0.098	0.900	39.2	<.0001
	3	w390	0.034	0.934	19.8	<.0001
	4	w437	0.030	0.964	32.1	<.0001
	5	w582	0.014	0.978	22.6	<.0001
	6	w365	0.007	0.984	14.9	0.000
	7	w366	0.004	0.988	10.6	0.003
	8	w451	0.006	0.994	31.6	<.0001
	9	w387	0.002	0.995	11.0	0.002
	10	w703	0.001	0.996	9.3	0.005
	11	w570	0.001	0.997	11.4	0.002
	12	w541	0.001	0.998	9.0	0.006
	13	w649	0.000	0.998	8.0	0.009
	14	w733	0.000	0.999	9.3	0.005
Greening	1	w681	0.942	0.942	392.0	<.0001
	2	w672	0.047	0.989	98.4	<.0001
	3	w517	0.004	0.993	10.7	0.003
Greening 1st der.	1	w697	0.964	0.964	640.9	<.0001
	2	w758	0.020	0.984	28.4	<.0001
	3	w578	0.011	0.995	50.2	<.0001
	4	w763	0.002	0.997	17.1	0.001
	5	w363	0.000	0.999	12.2	0.002
	6	w711	0.000	1.000	8.0	0.011
	7	w738	0.000	1.000	9.3	0.007

Table 3-7. Continued

Disorder	Step	Variable entered	Partial R-square	Model R-square	F value	Pr > F
	8	w405	0.000	1.000	9.8	0.007
	9	w747	0.000	1.000	5.1	0.040
	10	w562	0.000	1.000	8.3	0.012
Sunscald	1	w786	0.083	0.918	22.2	0.000
	2	w773	0.054	0.972	40.1	<.0001
	3	w589	0.005	0.985	7.2	0.014
	4	w588	0.003	0.992	7.3	0.014
	5	w629	0.002	0.994	7.0	0.016
	6	w787	0.002	0.996	9.5	0.006
	7	w758	0.001	0.997	6.3	0.023
Sunscald 1st der.	1	w729	0.730	0.730	65.0	<.0001
	2	w430	0.171	0.902	40.0	<.0001
	3	w483	0.062	0.964	37.9	<.0001
	4	w433	0.021	0.985	27.9	<.0001
	5	w428	0.007	0.991	16.2	0.001
	6	w553	0.002	0.993	4.9	0.039
Brown rot	1	w708	0.976	0.976	1044.5	<.0001
	2	w487	0.007	0.982	9.2	0.006
	3	w712	0.011	0.993	37.9	<.0001
Brown rot 1st der.	1	w567	0.810	0.810	110.6	<.0001
	2	w579	0.106	0.915	31.1	<.0001
	3	w433	0.039	0.954	20.4	0.000
	4	w662	0.022	0.976	21.2	0.000
	5	w717	0.008	0.984	10.1	0.004
	6	w759	0.004	0.988	6.8	0.017
	7	w405	0.005	0.992	11.9	0.003
	8	w439	0.003	0.996	13.6	0.002
	9	w737	0.001	0.998	11.3	0.004
	10	w671	0.001	0.999	13.4	0.002
	11	w434	0.001	1.000	13.6	0.002
	12	w718	0.000	1.000	10.4	0.006
	13	w390	0.000	1.000	12.2	0.004
	14	w482	0.000	1.000	5.8	0.032
	15	w689	0.000	1.000	9.7	0.009
Growth cracking	1	w670	0.041	0.857	7.4	0.011
	2	w461	0.106	0.963	72.4	<.0001
	3	w673	0.016	0.980	19.0	0.000
	4	w400	0.007	0.986	10.6	0.004
	5	w401	0.003	0.989	5.4	0.030
	6	w669	0.003	0.991	6.4	0.019

Table 3-7. Continued

Disorder	Step	Variable entered	Partial R-square	Model R-square	F value	Pr > F
Growth cracking 1st der.	1	w475	0.471	0.471	23.2	<.0001
	2	w460	0.270	0.741	26.0	<.0001
	3	w651	0.130	0.871	24.2	<.0001
	4	w520	0.055	0.926	17.2	0.000
	5	w440	0.034	0.961	19.1	0.000
	6	w603	0.015	0.976	13.1	0.002
	7	w579	0.006	0.982	7.2	0.015
	8	w459	0.006	0.988	8.5	0.009
	9	w427	0.003	0.991	5.6	0.029
	10	w770	0.002	0.993	5.6	0.030
	11	w685	0.002	0.995	5.1	0.038
	12	w638	0.002	0.996	7.1	0.018
	13	w387	0.001	0.999	8.5	0.012
	14	w512	0.001	0.999	12.0	0.005
	15	w381	0.000	1.000	21.1	0.001
	16	w479	0.000	1.000	6.5	0.029
	17	w556	0.000	1.000	5.6	0.043
	18	w800	0.000	1.000	14.0	0.005

Table 3-8. ‘Fabula’ wavelength selection of sample sets

Disorder	Correlation coef.	B-coefficient	SMLR
Internal Bruising	622 – 701 nm	365, 371, 373, 374, 384, 390, 394, 400, 425, 464, 692, 709, 714, 732, 735, 768, 787, 795, 799 nm	435, 791, 795 nm
I.B. 1st Der.	-	530, 605, 650, 666, 730, 790 nm	408,435, 456, 531, 742 nm
Shatter	360 - 420, 493 – 640 nm	360-400, 445-455, 475-486, 500-516 nm	376, 379, 382, 383, 386, 432, 438, 471 nm
Sh. 1st Der.	-	360-371, 380-425, 436-448, 455-465, 470-480 , 482-510 nm	499, 500, 504, 613, 629,648, 654, 688, 690, 722, 790 nm
Greening	380 – 710 nm	360, 371, 379, 384, 760, 762, 767, 774, 800 nm	503, 720 nm
Gr. 1st Der.	-	440, 463, 478, 506, 530, 670, 722, 748, 758, 767, 768 nm	510, 533, 625, 688 nm
Sunscald	490 – 700 nm	362-365, 371, 397, 777, 780, 788-798 nm	432, 446 nm
Sun. 1st Der.	-	599, 600, 606, 610, 682, 711, 718, 722, 726, 748, 780, 787, 788, 797, 798 nm	417, 449, 474, 512, 610, 611, 711, 737 nm
Brown Rot	360 – 800 nm	365, 366, 370-375 nm	688, 689 nm
B.R. 1st Der.	-	440, 470, 533, 566, 576, 589, 594, 607, 608, 646, 676, 677, 725, 787 nm	421, 518, 543, 625, 650, 792nm
Growth Cracking	360 – 800 nm	361, 363, 366, 371, 373, 382, 390, 394, 787, 790, 795 nm	477, 486, 516, 517, 543, 545, 547 nm
G.C. 1st Der.	-	473, 438, 536, 602, 631, 643, 645, 677, 711, 722, 729, 733, 756, 787, 790 nm	473, 510, 528, 529, 769 nm

Table 3-9. ‘Red la soda’ wavelength selection of sample sets

Disorder	Correlation coef.	B-coefficient	SMLR
Internal Bruising	600 – 800 nm	363, 365, 370, 371, 380, 390, 397, 714, 766, 770, 782, 787, 790 nm	763, 774, 776, 784, 788 nm
I.B. 1st Der.	-	462, 465, 566, 588, 683, 687, 782 nm	412, 484, 640, 648, 650, 681, 705, 786 nm
Shatter	360 – 660 nm	360-384, 423-462, 514-579nm	398, 403, 514, 568, 588 nm
Sh. 1st Der.	-	360-371, 397-405, 427-436, 470-480, 488-520 nm	471, 479, 502, 576, 585, 621, 625, 642, 788 nm
Greening	510-570 nm	618-698 nm	675, 680 nm
Gr. 1st Der.	-	461, 463, 475, 497, 530, 680-715, 725, 735, 744, 750, 797 nm	391, 650, 673, 730 nm
Sunscald	360-480, 620-710nm	360, 363, 366, 644, 650, 683, 686, 799, 800 nm	433, 435 nm
Sun. 1st Der.	-	512, 527, 540, 687, 711, 725 nm	425, 444, 530, 608, 675, 750 nm
Brown Rot	360-800 nm	361, 378, 382, 384, 416, 787, 800 nm	607, 665 nm
B.R. 1st Der.	-	507, 533, 657, 670, 673, 688, 709, 713, 726, 736, 774, 777, 790, 791, 799 nm	442, 615, 629, 631, 776, 781 nm
Growth Cracking	360-460, 620-800nm	402, 458, 516, 533, 566, 662, 685, 713, 722, 746, 750, 754, 777, 790, 791 nm	381 nm
G.C. 1st Der.	-	433, 622, 625, 633 nm	433, 622, 625, 633 nm
Insect Damage	360-480, 640-800nm	363, 371, 375, 376, 380, 465, 507, 527, 750, 777, 783, 787, 792, 797, 800 nm	800 nm
I. D. 1st Der.	-	420, 436, 502, 512, 519, 568, 574, 580, 657, 670, 690, 700, 738, 740, 770, 787, 793 nm	549, 586 nm

Table 3-10. Combined wavelength selection of sample sets

Disorder	Correlation coef.	B-coefficient	SMLR
Internal Bruising	600-800 nm	370, 373, 378, 383, 392, 710, 747, 752, 762, 782, 790, 793 nm	No wavelengths selected
I.B. 1st Der.	-	400, 420, 660, 676, 709, 728, 787, 793 nm	427, 442, 443, 540, 558, 576, 589, 667, 682, 716, 791, nm
Shatter	360-800 nm	360-397, 440-460, 473-484 nm	378, 362, 388, 395, 422 nm
Sh. 1st Der.	-	449-466, 553, 713, 722, 752, 768 nm	365, 366, 387, 388, 390, 437, , 451, 541, 570, 582, 649, 672, 703, 733 nm
Greening	400-480, 600-700nm	670-683 nm	517, 672, 681 nm
Gr. 1st Der.	-	397, 406, 442, 473, 725, 748, 798 nm	363, 405, 562, 697, 711, 738, 747, 758, 763 nm
Sunscald	360-480, 620-710nm	722, 746, 764, 766, 770, 780, 788, 792, 800 nm	588, 589, 629, 758, 773, 786, 787 nm
Sun. 1st Der.	-	680, 708, 713, 720, 750, 774, 777, 788, 790, 797 nm	428, 430, 433, 483, 553, 729 nm
Brown Rot	360-600 nm	370, 372, 373, 383, 392, 747, 762, 782, 790, 793 nm	487, 708, 712 nm
B.R. 1st Der.	-	423, 530, 660, 683, 790, 797 nm	390, 405, 433, 434, 439, 482, 567, 579, 662, 671, 689, 717, 718, 737, 759 nm
Growth Cracking	360-460, 620-800nm	378, 389, 398, 404, 704, 722, 734, 738, 752, 778, 782, 787, 789, 797, 800 nm	400, 401, 461, 669, 670, 673 nm
G.C. 1st Der.	-	371, 413, 442, 475, 540, 579, 665, 686, 730, 753, 787, 789, 787 nm	381, 387, 427, 440, 459, 460, 475, 479, 512, 520, 556, 579, 603, 638, 651, 685, 770, 800 nm

CHAPTER 4
CONCLUSIONS

Four types of damage were observed in the impact drop tests of the two varieties; skinning, blackspot, external and internal shatter. The major type of external mechanical damage in the harvesting and packaging operations for 'Fabula' was skinning; while the major type of damage for 'Red La Soda' was external shatter. Skinning tests performed on 'Fabula' and 'Red La Soda' 7 days before vine-kill showed average percentages of potatoes detected with skinning damage at 77.8% and 5% with 'Red La Soda' maintaining a fairly consistent low skinning rate and severity throughout the study. 'Fabula', on the other hand, started out with a very high skinning rate which dropped significantly for harvest periods following vine-kill with severity of skinning dropping dramatically as a result of only 7 days of wait. The highest USDA skinning rating was 'Slightly skinned' for 'Red La Soda' which maintained high skinning resistance throughout packaging line skinning, while 'Fabula' started out the USDA rating 'Badly skinned' 7 days before vine-kill occurred and improved to 'moderately skinned' right before vine-kill which significantly lowered skinning which occurred.

During testing, incidences and severity of mechanical damage generally increased with drop height for both varieties, with blackspot bruising occurrence switching to external shatter at higher drop heights for the variety 'Red La Soda'. Comparison of data indicated that low moisture content flesh resulted in higher incident rates of blackspot bruising in 'Fabula', while high moisture content flesh resulted in higher incident rates of shatter in both 'Fabula' and 'Red La Soda'. Impacts of greater height resulted in more severe damage for all types of damage, but did not always result in larger groups of tubers developing bruising or shatter damage. Both varieties showed resistance to the development of bruising and shatter the 7 days before vine-kill

was performed, but showed their greatest incidence and severity the day before vine-kill was performed. Of the two varieties, ‘Red La Soda’ was much more likely to develop bruising damage after vine-kill and with greater severity; which lowered as the time after vine-kill increased. The significant drop in mechanical damage which occurred with just 7 days of skin set after vine-killing would allow farmers to harvest earlier than the standard 2-3 weeks if desired; harvesting earlier than the standard time would result in a small, but noticeable, increase in damage. But if weather conditions or insect presence could result in tuber plants left in the soil being exposed to circumstances that would threaten tuber health; it is advised that potato tubers be harvested after a shorter period of skin set.

A wide range of spectroscopic techniques have been widely used for analysis of food products. Spectral reflectance in the range of 360-800 nm were collected for potato samples of the varieties ‘Fabula’ and ‘Red La Soda’ and then analyzed using the correlation coefficient spectrum, PLS and SMLR in order to find important wavelengths to establish calibration models for predicting the potato tuber disorders; internal bruising, shatter, greening, sunscald, brown rot, growth cracking and insect damage. The range used for disorder evaluation (360-800 nm) was chosen after determining that this range had a lower dependence of moisture content after analyzing data in the range between 200-2500 nm. All disorder data for ‘Fabula’ and ‘Red La Soda’ had spectral ranges within the evaluated wavelengths (360-800 nm) which had high correlation coefficients above 0.4. Analysis of the data using PLS and SMLR, endorsed the reduction of the wavelength ranges necessary for prediction of damage to 360-480 nm and 600-800 nm. This would mean that spectral wavelength scans could be concentrated on these areas in order to calibrate models for prediction of damage faster on a packaging line. Prediction models created with PLS allowed for fairly accurate prediction of damaged tubers with SEP below 3%

for all models created using data for ‘Fabula’, ‘Red La Soda’ and a combination of both varieties.

Each disorder, except for growth cracking and insect damage, had a unique cause of reflectance changes associated with damage that occurred. Internal bruising was associated with the production of melanin which effected wavelengths around 475 nm for both varieties. Shatter damage resulted in an increase of exposure to potato tuber starches below the surface of the skin which was missing. Greening reflectance was changed by the increased presence of chlorophyll, solanine and other photosynthesis chemicals; which had significant effects on the photosynthetically active range of 450 nm to 670 nm. Sunscald was associated with the radiative burning of tuber flesh which caused chemical changes in the surface and subsurface. Brown rot was influenced by the bacterial rot that caused brown-grey discoloration and the development of creamy pus. Growth cracking and insect damage reflectance changes were both the result of H_2O_2 development that resulted in tuber suberization at the point of damage.

The study demonstrated the potential for predicting damage and disorders in potatoes using VIS/NIR spectral data, but results of prediction models would need to be improved with additional data points in order to reduce the error which occurred when predicting damage levels on healthy undamaged samples. The experiment showed that the selected wavelength ranges in the VIS/NIR range could be used for successful prediction of damage and disorders in potato samples and used to develop rapid and objective damage prediction systems for fresh market ‘Fabula’ and ‘Red La Soda’ potatoes.

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BIOLOGICAL SKETCH

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