The Effects of Potato Virus Y Strains on Quality of Four Potato (*Solanum tuberosum* L.) Varieties in Storage

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Authorization to Submit Thesis

This thesis of Marcus Andros, submitted for the degree of Master of Science with a Major in Plant Science and titled "The Effects of Potato Virus Y Strains on Quality of Four Potato (*Solanum tuberosum* L.) Varieties in Storage," has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

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Abstract

Potato (Solanum *tuberosum* L.) is prone to infection by viral pathogens due to successive cycles of vegetative propagation. *Potato virus Y* (PVY) is an economically important virus and has recombinant strains that may affect potato yield and quality differently. In a two year study, four varieties, Alturas, Russet Burbank, Ranger Russet, and Umatilla Russet, were grown in a screen-house to prevent in-season spread and mixing of PVY strains among plants. Leaves were manually inoculated with PVY^{NTN}, $PVY^{N\text{-}Wi}$ and PVY^{O} when plants were 20-25 cm in height. Tubers from each plant were harvested, stored at 8.9° C and evaluated for external and internal PVY symptoms at harvest and after 5 and 10 months in storage. Observed tuber symptoms included: external rings, internal rings, internal spots and necrosis under the skin. The center plank from each tuber was fried at 191° C for 3.5 minutes and reflectance and fry quality measured. Tuber samples were assayed for the presence of specific PVY strains using ELISA and RT-PCR. In year one, none of the varieties infected with $PVY^{N\text{-}Wi}$ showed symptoms at harvest or throughout storage, except tubers of Alturas which had 41% incidence after 10 months in storage. All varieties exhibited symptoms, except Russet Burbank tubers, at harvest when infected with PVY^{O}. In year two, none of the varieties showed symptoms when infected with PVY^{O} at harvest or throughout storage. Fry quality was not affected by infection of PVY^{NTN} and $PVY^{N\text{-}Wi}$, and in some cases exhibited better quality compared to healthy and PVY^{O} infected tubers. PVY had limited effect on fry quality unless raw tuber symptoms were present. Results from these evaluations will help identify the potential risk of a particular variety having tuber quality degradation if infected with a specific PVY strain.

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Dedication

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Chapter 1: Literature Review

Potato (*Solanum tuberosum* L.) is the third most important food crop in the world, following wheat and rice (Visser et al. 2009). The United States national acreage for potatoes harvested in 2015 was 1,053,300 (NASS 2015b), while Idaho accounted for 324,000 of those harvested acres (NASS 2015a). Potato is a crop that is prone to infection by viral diseases due to successive cycles of propagation (Nie et al. 2015). Currently, the most important virus affecting potato is Potato Virus Y (PVY) (Basky and Almási 2004). In the Pacific Northwest (PNW) area of Idaho, Oregon and Washington, potatoes have a growing season from spring through summer, with harvest beginning at the end of summer months and into fall. Since it is only a single growing season, storage of potatoes plays a vital part in the PNW to maintain the supply of potatoes in markets all year long.

Common end uses include fresh market or processed potatoes. Processing potatoes are used for mostly French fries and other products such as chips and made up 70% of the total volume of potatoes used in the PNW in 2015 (USDA 2016a). Important characteristics of potatoes for fresh and processing uses include external appearance, size, shape, skin texture and pigmentation, flesh color, internal and external defects, and dry matter content (Rubatzky and Yamaguchi 2012). Sugar content, especially reducing sugar levels, are very important for processing potatoes in order to produce an acceptable fry color.

Each potato variety is used for particular traits such as disease resistance or storability. General storability and other traits differ so to account for these inherent differences in the industry four varieties (Alturas, Russet Burbank, Ranger Russet and

Umatilla Russet) were selected for this study to evaluate how each variety would react to infection with three most common strains of PVY (PVY^{NTN}, PVY^{N-Wi} and PVY^{O}) (Funke et al. 2017). Of particular importance to the PNW is the impact of in-season PVY on processing quality in the top processing varieties grown. Producing a quality crop and maintaining quality in storage is important to the economic value of the harvested potato crop. The prevalence of PVY in the PNW prompted the need to better understand the potential impact of the virus on processing quality.

Current control of PVY is primarily by seed certification programs (Blanco-Urgoiti et al. 1998). The certification program ensures that seed planted have levels of disease within the mandated tolerances. Seed lots planted for re-certification must have levels of PVY within the state's tolerances. Commercial crops in Idaho must be planted to certified seed, but the grower can decide if the level of PVY in the selected seed lot is acceptable. There is no maximum tolerance level of PVY for commercial crops, only for certified seed crops. This may lead to higher than desirable levels in the Idaho commercial acreage.

Another common way for long term control of PVY is by genetic resistance, which entails breeding for resistance to PVY. There are two types of resistant genes that may be conferred in potato. There is extreme resistance which is conferred by R genes (Karasev and Gray 2013a) which is defined as either the complete failure of the virus to replicate in the host, or replication is at such an extremely low level that the virus is not detected. The other type of resistance is hypersensitive resistance (HR). HR is conferred by N genes and is defined as a limited replication of the virus that leads to local visible lesions in the leaf which stops it from moving throughout the plant or results in development of systemic necrotic reaction throughout the plant. HR is more prone to breaking down due to being strain specific and sensitive to environmental conditions such as temperature.

Varieties

Four varieties were selected for this study based upon production of each in the PNW for processing. Alturas, Russet Burbank, Ranger Russet and Umatilla Russet are all widely used for processing; Russet Burbank is also a variety used for the fresh market.

Alturas was first grown in Aberdeen, Idaho in 1989 and originally selected for dehydration processing (Novy et al. 2003). It is also utilized for processing into French fries due to its high yield and tuber specific gravity. The pedigree of Alturas includes the varieties of Atlantic, Lemhi Russet, Lenape, Nooksack, Norgold Russet, Pioneer, Viking, and Wauseon. Alturas is known for producing a high yielding crop, surpassing Ranger Russet and Russet Burbank. It is late maturing (approximately 2-3 weeks after Russet Burbank). Overall Alturas is resistant to Verticillium wilt (*Verticillium dahlia*) and early blight (*Alternaria solani*) but is susceptible to potato leafroll virus (PLRV), potato virus X and Y (PVX and PVY), Erwinia soft rot, Columbia root-knot nematode (*Meloidogyne chitwoodi*) and bacterial ring rot (*Clavibacter michiganensis* subsp. *Sepedonicus*). Alturas was released in 2002 (Novy et al. 2003). Alturas is known to produce the typical PVY mosaic foliar symptoms, vein burning and possibly plant death (Hamm et al. 2010), and was found partially resistant to the PVY^{O} strain (Funke et al. 2017; Rowley et al. 2015). Out of all potato acres grown in Washington, Oregon, and Idaho Alturas acreage made up 6%, 4.7%, and 1.2% respectively in 2015 (USDA 2015).

The variety Russet Burbank was introduced in 1873 by Luther Burbank. It currently accounts for the highest number of planted acres in North America and is worth $1.5 billion annually (Brown 2015). Luther Burbank planted the 23 true seeds from the Early Rose variety and each seed was germinated and transplanted to his garden. After a second year or propagation the number 15 plant was selected for the astounding yield of larger tubers, good storability, and good eating quality. Russet Burbank is susceptible to the PVY strains evaluated in this study (Funke et al. 2017) and develops mild mosaic foliar symptoms to PVY^{O} but not to PVY^{NTN} (Nie et al. 2012). Russet Burbank acreage was 32.6% of total acreage in Washington, 18.3% in Oregon, and 53.7% in Idaho in 2015 (USDA 2015).

The USDA Agricultural Research Service and the agricultural experiment stations of Idaho, Oregon, Washington and Colorado released Ranger Russet in 1991. Some of the characteristics of Ranger Russet include medium to late maturing crop, a long russet shape and excellent processing quality (Love et al. 1992). Ranger Russet is susceptible to two of the PVY strains evaluated in this study, PVY^{NTN} and $PVY^{N\text{-}Wi}$ (Funke et al. 2017), and is partially resistant to PVY^{O} strain (Funke et al. 2017; Rowley et al. 2015). It exhibits a shock reaction or a plant die-back response to PVY^{O} but with PVY^{N} it produces a much less severe reaction (Crosslin et al. 2006). Ranger Russet is considered highly sensitive to PVY^{NTN} which causes mild to strong plant mottling that is sometimes so severe that the plant does not produce tubers (McDonald and Singh 1996). Ranger Russet acreage was 6.6% of acreage in Washington, 14.9% in Oregon, and 14.3% in Idaho in 2015 (USDA 2015).

The variety Umatilla Russet started as a cross in 1982 by J.J. Pavek in Aberdeen, Idaho and was selected at Powell Butte, Oregon in 1984. The Agricultural Experiment Stations of Oregon, Idaho and Washington and the USDA released the variety in 1998. Umatilla Russet is a moderately late maturing crop that is especially suitable for frozen French fry processing (Brandt et al. 2003). It is also acceptable for use in baking and boiling. Overall yields for Umatilla Russet are similar to Russet Burbank, but Umatilla Russet produces higher marketable yields than Russet Burbank. Umatilla Russet tubers have lower glycoalkaloid content when compared to Russet Burbank. It has higher vitamin C and protein content when compared to Russet Burbank and Russet Norkotah. The variety is more susceptible to shatter bruise but produces less growth cracks when compared to Russet Burbank (Mosley et al. 2000). Umatilla Russet is resistant to PVX and partially resistant to PVY^{O} and PVY^{NTN} strains, but not to $PVY^{N\text{-}Wi}$ (Funke et al. 2017). Foliar symptoms of PVY are not always clearly presented. Umatilla Russet comprised 15.4% of total acreage for Washington, 16.5% for Oregon, and 2.1% for Idaho in 2015 (USDA 2015).

Potato Virus Y

Viruses are obligate parasites that require a host to complete their life cycle (Blanchard et al. 2008). Potato virus Y (PVY) is one of the most economically important viruses and plant pathogens (Blanchard et al. 2008). PVY exists in many different plant hosts and, importantly to the potato industry, different species in the solanaceous family. The virus also exists as a complex of at least nine different strains (Funke et al. 2017;

Rowley et al. 2015). PVY strains can be distinguished by the reactions towards a series of resistance genes in potato and tobacco, and also serologically and based on molecular properties (Karasev and Gray 2013b).

Among the nine different strains of PVY the most common in the U.S. are PVY^{O}, $PVY^{N:O}$, $PVY^{N\text{-}Wi}$, and PVY^{NTN} (Benedict et al. 2015; Funke et al. 2017). PVY^{O}, PVY^{C}, and PVY^{N} are considered the parental strains, while PVY^{NTN}, $PVY^{N:O}$, and $PVY^{N\text{-}Wi}$ are the new recombinants of the parental strains (Dupuis 2016; Gray et al. 2010) which are common strains in the PNW region (Funke et al. 2017). Although PVY infects a range of host plants, that include potato, tomato, pepper and tobacco, many of the strains are host specific, for instance many isolates of the PVY^{C} strain group are adapted to pepper and cannot infect potato (Green et al. 2017). It is also important to remember other potato viruses such as Potato leafroll virus (PLRV), Potato virus X (PVX), Potato virus A (PVA) and Potato virus S (PVS) can infect potato plants. Plants could be infected with a single virus or as a mixture of virus infections within the potato crop (Agindotan et al. 2007).

Potato virus Y is a virus that can be vegetatively transmitted (seed-borne) and can also affect plants in-season through aphid vector or mechanical transmission. Vegetative or seed-borne transmission occurs when a PVY infected tuber is planted as seed for the new crop and the resulting plant is infected with PVY. Planting seed that is either clean or low in virus infection helps control or prevent seed-borne infection (Love et al. 2003a). This project focused on the impact of current season infection by mechanical transmission.

Aphid vectored PVY transmission occurs in a non-persistent, stylet-borne manner, meaning aphids acquire the virus in short feeding times and pass to healthy plants in a short duration with no latent period (Mondal et al. 2017). More than 50 colonizing and non-colonizing aphid species can transmit PVY in a non-persistent manner. Potato viruses can overwinter in tubers left in the ground at harvest and subsequently in the emerged volunteer plants the following year (Thomas 1983). From previous studies looking at the efficiency of aphid transmission of PVY, the green peach aphid (*Myzus persicae)* has been the most efficient (Boquel et al. 2011). Other species of aphids can transmit PVY but not as efficiently as the green peach aphid. Previous studies observed other non-colonizing aphids such as cereal aphids and *Capitophorus elaeagni* (no common name) may be the primary source of vectoring and spreading of PVY if the green peach aphid is being controlled. Though insecticides are applied to the crop, applications are only expected to control colonizing aphids (Halbert et al. 2003).

Potato plants infected with PVY from primary (seed borne) or secondary (in-season) infection have different foliar reactions depending upon PVY strain and potato variety. Some plants will become stunted in growth and may become yellow in color. This color change may attract aphids to the plant where they acquire the virus and can lead to further spread. The difference in contrast between wavelengths reflected by the bare ground and the plant canopy may also attract aphids to the edges of fields (Boquel et al. 2017). The wavelengths of green, orange, and yellow are stimulating wavelengths for aphids with a preference to yellow. The practice of rogueing PVY infected plants is effective when done before the migration of aphids, but sometimes current season spread symptoms are not visible before this time. Rogued plants should be discarded away from the field as they may remain a PVY source.

The control of vectors is often the best form of virus control, which include oils and insecticides. In a study performed by Wrobel (2012), the use of mineral oil and rapeseed oil as a protective spray against aphid probing was tested. Mineral oil was found to be more effective than rapeseed oil (Wrobel 2012). Mineral oil has been studied as a way to prevent PVY spread but is not recommended to be used alone. It has a higher efficacy when combined with pyrethroids (Loebenstein et al. 2013). Potyviruses such as PVY are transmitted in short feedings, lasting only seconds, and insecticides cannot work quick enough to prevent transmission of PVY (Loebenstein et al. 2013). Aphid transmission of PVY is very difficult to control and contributes to the higher than desired PVY levels in seed lots.

PVY is primarily transmitted by aphids during the season but there is also the potential of spread by equipment such as knives that are used for cutting seed. Previous research by Draper and Gudmestad (1992) demonstrated that PVY could be transmitted at very low levels by knives used for cutting seed. Research by Roberts (1950) looked at tomato and potato plants becoming infected through roots when inoculated with PVX. He hypothesized that potato plants could become inoculated with PVX when the roots where mechanically injured (Loebenstein et al. 2013). PVY might act similarly on plants and infect through the roots, but additional research needs to be performed.

Past research has been conducted with PVY^{O} on whether it can be spread through contact of infected leaves and equipment that passes through the field (Coutts and Jones 2015). Research showed that PVY^{O} spreads readily from infected plants to healthy plants by leaf to leaf contact and by a lesser amount from tuber to leaf contact. PVY^{O} remained infective in sap at room temperatures for up to 28 hours, for up to 6 hours after drying on wood and cotton, and up to 24 hours on tires and metal. The potential and likelihood for mechanical spread of PVY needs additional research to better understand this risk.

The reaction of a potato plant infected with PVY can depend upon the age of the plant at the time of inoculation. Older plants often show a stronger resistance to infection compared to younger plants due to physical barriers such as trichomes and wax that prevent insects from probing or feeding and delivering the virus (Choi et al. 2017). Previous studies show that temperature affects the amount of time it takes for the virus to become systemic in young plants. Systemic infection of PVY in young potato plants was affected by temperature; at 20° C it was 14 days and at 28° C it was 5.7 days for systemic infection to occur (Choi et al. 2017). Therefore, seasonal temperatures may affect the incidence of the virus in the potato crop. Not only will the seasonal condition influence PVY infection, but also infection will be dependent upon the variety. Each strain of PVY may react differently in the various potato varieties currently grown. In some varieties, the infection of PVY may cause more severe reactions than other varieties. In some varieties, PVY^{O} induces a clear localized reaction while in some varieties, such as Ranger Russet, PVY^{O} is more severe and the plant may completely die not long after inoculation (Crosslin et al. 2006; Funke et al. 2017; Rowley et al. 2015).

After the virus infects the leaves systemically, it is translocated to the progeny tubers. Once the virus has entered the phloem it moves rapidly (cm/h) towards the growing regions of the plant, such as the tubers and roots (Mehle et al. 2004). Research has shown that PVY^{N} is better at translocating than PVY^{O} (Beemster 1976). PVY translocation occurs faster in young plants than in old plants. The later the inoculation after the time of planting the less yield will be impacted (Dupuis 2016). There is a process in potato plants called mature plant resistance where plants inoculated late in the growing season with a virus such as PVY are less likely to have infected progeny tubers when compared to plants inoculated early in the growing season. It is also known that not all progeny tubers will be PVY positive from a PVY positive plant (Gibson 1991). Mature plant resistance develops later against PVY^{N} compared to PVY^{O} and therefore making it potentially more difficult to control PVY^{N} (Weidemann 1988).

PVY affects total potato yield and tuber quality causing an economical loss for both seed producers and potato producers supplying potatoes to the fresh and processed markets (Benedict et al. 2015; Fomitcheva et al. 2009; Funke et al. 2017). The addition of extra nitrogen fertilizer may mask the foliar symptoms of PVY, but does not help reduce the risk of yield loss (Whitworth et al. 2006). The yield loss due to seed-borne PVY infection depends upon variety. Seed-borne PVY infection can cause yield reduction in some varieties even if the symptoms are mild. Marketable yields were reduced more than total yield in Shepody and Russet Norkotah which express mild foliar symptoms (Hane and Hamm 1999). Yield loss due to PVY can range depending on the type of infection. If the infection is current season spread there is little yield loss (Loebenstein et al. 2013). If the current season infection occurs after flowering the yield loss is lowered compared to infection earlier in the plant development. If the infection is seed-borne then the yield loss will be higher. To control the seed-borne issue there are seed certification programs established with rules to help maintain low rates of virus infection in planted seed.

Depending upon variety, the common strain of PVY^{O} can cause yield loss with seed-borne infection. Past research has shown that seed borne infected Russet Burbank and Russet Norkotah plants each yielded 50% less than non-infected plants and current season infected plants showed 24% to 30% lower yields (Mondjana et al. 1993). Other research showed seed-borne effects of PVY on Russet Norkotah plants produced lower total yield, yield of large tubers, fewer tubers per plant, and lower specific gravity when compared to virus free plants (Rykbost et al. 1999). In this same study, seed-borne infection did not affect the rate of emergence or final stands. Senescence was also observed to be earlier in Russet Norkotah with seed-borne PVY infection. Other research with Russet Norkotah showed there was no effect on total or marketable yield when plants were infected in season (Whitworth et al. 2010).

PVY can cause a number of symptoms in potato foliage and tubers. Foliar and tuber symptoms can differ depending upon the potato variety and the PVY strain. PVY^{N} strain tends to be less symptomatic than PVY^{O} in potato plants (Gray et al. 2010). PVY^{O} will induce easily recognizable mosaic symptoms in most varieties of potato, but PVY^{O} is being displaced by tuber necrotic strains, mainly PVY^{NTN} and $PVY^{N\text{-}Wi}$ (Funke et al. 2017). It is important to note that PVY^{N} is a strain that seems to be disappearing from potato in the U.S. and Canada and that PVY^{O} is also starting to become less prevalent in many potato production areas, whereas the recombinant strains of PVY^{NTN} and $PVY^{N\text{-}Wi}$ are becoming more prevalent in potato production areas (Funke et al. 2017; Karasev and Gray 2013b). In general, recombinant strains of PVY tend to induce foliar symptoms milder than that of PVY^{O} (Karasev and Gray 2013b). The common or original strain, PVY^{O}, has primary symptoms of leaf mottling and necrosis and can cause a mosaic look to the foliage, but can also cause symptoms of crinkling and plant dwarfing (Whitworth et al. 2010). PVY^{N} produces milder foliar symptoms than does PVY^{O} (Crosslin et al. 2006). Foliar symptoms with PVY^{NTN} may include vein necrosis, leaf drop, necrotic streaks on stems, or systemic necrotic rings. The response that varieties have in the foliage generally parallels to the sensitivity of the tubers to producing symptoms of potato tuber necrotic ringspot disease (PTNRD). This means that if the variety develops strong foliar symptoms then it tends to be more sensitive to tuber disease and symptoms development (McDonald and Singh 1996).

PTNRD is not limited to just PVY^{N} strains since PVY^{O} and $PVY^{N\text{-}Wi}$ strains may also cause PTNRD (Gray et al. 2010). PTNRD is characterized by the appearance of external rings on tubers that protrude and later become sunken and necrotic. These symptoms can become more pronounced during time in storage (Le Romancer and Kerlan 1994). Milder forms of PTNRD can also be expressed but the severity and type of tuber symptoms are influenced by variety, virus strain, environment, and type of infection (Karasev and Gray 2013a). The recombinant strains of PVY are more likely to cause PTNRD of varying severity based on the variety that is infected (Mondal et al. 2017). Some strains such as $PVY^{N:O}$ can still cause external rings but they are subtle and could easily be looked over (Piche et al. 2004). It has also been shown that PVY^{NTN} and PVY^{O} can cause internal tuber symptoms such as brown spots, depending upon variety (Karasev et al. 2008). PVY^{NTN} is known to cause PTNRD where the tuber will develop superficial rings that initially are raised and later become sunken and necrotic (Loebenstein et al. 2013). PTNRD can cause internal and external discolorations that are not acceptable for processing potatoes. It is still unknown if non-symptomatic tubers will also have changes in processing quality.

Processing Quality and Storage

Processing quality plays a very large and important role in the end use of potatoes in the Pacific Northwest. In 2016 Idaho produced 6,319,449 metric tons of potatoes and 4,207,523 metric tons were used for processing (USDA 2017). There are two important quality characteristics of potatoes, starch content, which affects the cooked product texture, and sugar content, which affects the fried product color (Stark and Love 2003). High starch content, indirectly measured by tuber specific gravity, is favored for processing to ensure a good texture, higher yield of finished product and lower oil consumption (Lulai and Orr 1979). Tuber reducing sugars play an important part in determining fry color. The higher the reducing sugars the darker the fry color. Environmental factors such as air and soil temperature during the growing season can effect tuber specific gravity and cultural factors such as choice of variety, nutrient management, irrigation, tillage and disease management practices can also alter tuber specific gravity. PVY can be a stress to the plant that may lower tuber specific gravity, which will effect fry quality.

To ensure potatoes are available year-round they are stored after harvest until the following crop is available. This allows growers or processors to use the potatoes throughout the year. The quality of tubers is influenced before storage by such factors as variety, growing techniques, soil type, weather conditions during growth, disease, maturity of tubers at the time of harvest and damage to tubers during harvest and loading into the storage. It is important that a storage building provide dark conditions with proper ventilation, humidity and temperature to help maintain the overall quality of the crop (Olsen 2014). The storage structure and management program will vary depending on the use of the crop and how long the potato will be stored. No matter the end use of the potato crop going into storage, the need to minimize losses is important. Losses during storage are mainly caused by respiration, sprouting, evaporation of water from tubers, spread of diseases, changes in chemical composition and physical properties of the tuber from extreme temperatures (Eltawil et al. 2006). All of the above conditions depend on the storage and its management.

Commercial growers must also contend with possible internal and external defects. This can be due to the occurrence of PVY^{N}, PVY^{NTN}, and $PVY^{N:O}$ strains (Hamm et al. 2010). PVY^{N} strains tend to produce visual tuber symptoms. These internal and external defects may lead to processed potatoes being downgraded or rejected for use, both of which have economic consequences. High temperature has been found to influence the development of tuber necrosis caused by PVY^{NTN} during the growing and storage period (Dolnicar et al. 2011). Temperatures around 4° C in the first month after harvest can be therefore used to prevent the development of necrosis in susceptible varieties. The longer the tubers were kept at 4° C before being brought into room temperature the less necrotic symptoms that developed. Low temperature storage is not always an option for process potatoes.

Stressful conditions not only cause malformed tubers but can also cause internal quality problems (Iritani 1981). One tuber quality issue is a defect that is expressed after frying known as mottling (Jankowski et al. 1997). Mottling is expressed as non-uniform browning in fried potatoes. This defect typically appears after time in storage and depending on the incidence and the severity can lead to rejection of a lot for processing. Another tuber quality issue can be sugar end development. There are three distinct causes of sugar end in potatoes. First, a stress early in the tuber development stage generally results in tubers with higher reducing sugars at the basal end. Second, a stress late in the growing season generally causes tubers to have accumulated reducing sugars in the apical end. And third the stress associated with premature plant death typically causes tuber to have sugar ends in the basal or stem end (Iritani et al. 1973).

It is the industry standard for processing potatoes to be light in fry color. Previous research has shown that fry color darkens as conditioning temperatures decreased from 9 to 4.5° C (Driskill et al. 2007). Tubers were most sensitive to low temperatures during the initial conditioning period following wound healing which led to a loss in processing quality. The typical standard for storing potatoes for the frozen French fry market is 8 to 9° C, and it represents a compromise that limits the negative effects of higher temperatures on increased weight loss, disease pressure, and sprouting while at the same time minimizing cold-induced sweetening and the deterioration of processing quality. At low storage temperature glucose and fructose accumulate in tubers and these sugars react with free amino acids during the frying process to produce unacceptable dark processed fries and chips. This process of sugars turning to dark spots while being fried is known as the Maillard reaction and is a result of the reaction between reducing sugars and amino acids at high temperatures (Pritchard and Adam 1994). Low sucrose concentrations at harvest time normally ensures acceptable processing quality from long-term storage at intermediate temperatures. Stresses that happen during the growing season can alter tuber shape, size and fry quality (Iritani 1981). There is limited information on the effect of current season PVY infection on processing quality characteristics such as mottling, sugar ends and total reducing sugars.

It is important to remember that the health of the crop going into storage isn't going to get better. Storage is not a hospital, and it does not improve the quality of potatoes that are being stored (Brook et al. 1995). Knowing this, it is important to better understand how PVY infected tubers will respond in storage.

The objective of this research was to evaluate the impact of several PVY strains on tuber quality of four commonly grown potato varieties at harvest and in storage. By storing tubers harvested from inoculated plants, evaluations could be performed to determine if the incidence or type of tuber symptoms change after time in storage, if there is an impact on processing quality, and if asymptomatic tubers cause any quality concerns. This research will provide information to growers experiencing in-season PVY infection growing these processing varieties, and the risk of impacting tuber quality with time in storage.

Chapter 2: Materials and Methods

Potato varieties Alturas, Russet Burbank, Ranger Russet, and Umatilla Russet were grown for two years, 2015 and 2016, at Oregon State University Hermiston Agricultural Research and Extension Center (HAREC) in Hermiston, Oregon in an Adkins fine sandy loam soil (USDA 2016b). Virus free mini tubers (obtained from Valley Tissue Culture, Halstad, MN) were planted April 16, 2015 in 4 row plots (3.0 m) with 30 cm within-row spacing (year one). Plots were laid out in a randomized complete block design with 10 plants sub-replicates. Year two was planted April 19, 2016 using virus free mini tubers in 4 row plots (2.3 m) with 23 cm within-row spacing. Tubers were grown in a screen house (22 m x 11 m) to both mimic the field conditions for potato production and minimize any current-season spread of the virus by aphids. The experiment consisted of 16 treatments (4 varieties x 3 PVY strains and 1 non-inoculated control x 4 replications x 10 plants (sub replications) = 640 plants). Each of the four varieties was represented by 160 plants, with 40 plants inoculated of each strain, and 40 with the non-inoculated control, as first described by Funke et al. (2017).

All plants were sampled prior to inoculation and assayed for PVY using RT-PCR by R. Cating to confirm that no PVY was present. On May 27, 2015 and May 26, 2016, assisted with Funke et al. (2017) in mechanically inoculating the plants with three strains of PVY. These strains include, PVY^{O} (isolate Tb60), PVY^{NTN} (HR1), $PVY^{N\text{-}Wi}$ (N1), and non-inoculated control. Inoculum was provided from the University of Idaho isolate collection. Plants were approximately 20 to 25 centimeters at the time of inoculation (Funke et al. 2017).

Inoculum was made using 20 grams of leaves that were infected with each specific strain of PVY and 200 milliliters of buffer solution mixed in a blender. The blended inoculum was placed in 50 milliliter tubes and four grams of silicon carbide was added. Silicon carbide was added to assist in wounding the leaves for uptake of PVY. Inoculum was applied to one leaflet from three different leaves on each plant. If plants had multiple stems one leaflet from different stems were inoculated (up to 3). Leaflets were completely covered in inoculum using a sterile cotton swab (Fisher Scientific Hampton, NH). Plants were inoculated using one strain of PVY at a time. Control plants were not inoculated. On July 1, 2015 and June 21, 2016, approximately four and half weeks after inoculation three leaves from each plant were picked for strain testing. Strain testing was performed using ELISA and RT-PCR to assess for percent infection.

Growing Season

Plants were maintained by K. Frost (Oregon State University) throughout the growing season with standard agronomic, irrigation and pest control care typical for the area. See appendix (Table A.1) for specifics on the fertility program.

Post-Harvest

Tubers were hand harvested on August 31, 2015 and September 23, 2016. Tubers from individual plants were bagged in red mesh bags (33cm x 43cm, Associated Bag

Company, Milwaukee, WI) and labeled according to block, treatment, and plant number. Tubers were shipped to the Kimberly Research and Extension Center in Kimberly, Idaho within two days of harvest. Tubers were kept at 13.3 to 16.7° C after harvest and in transport to Kimberly, Idaho. Temperature was recorded during this time using data loggers (HOBO UX100 data loggers Onset, Bourne, MA. Model UX100-003).

On delivery of the tubers, weight of all tubers (kg/plant) from individual plants were recorded. Specific gravity was measured using plant 10 from each row of each block (if plant 10 was not available another positive plant was substituted) via weight in air/weight in water method of Schippers (Schippers 1976). Tubers were placed back in red mesh bags, stored in plastic mesh boxes (60.3 cm X 40 cm X 20.3 cm) and placed in a potato storage bin at the Kimberly Potato Research Building. Tubers were cured at 12.8 (+/- 0.1) °C and ramped down 0.3 °C per day to a final holding temperature of 8.9 (+/- 0.1) °C. Relative humidity was kept at 95% (+/- 3%) during the entire storage period. A thermal application of sprout inhibitor chlorpropham (CIPC; Sprout Nip 7A, Loveland Products, Inc. Greeley, Colorado) at 22ppm was administered on November 24, 2015 and November 22, 2016.

Evaluations

Evaluations for year one were performed on September 21, 2015 (harvest), January 26, 2016 (mid-storage), and June 14, 2016 (late-storage). Year two evaluations were conducted on October 3, 2016 (harvest), January 20, 2017 (mid-storage), and May 10, 2017 (late-storage). Time in storage was a split treatment.

For each evaluation, two tubers from each plant were individually weighed before the external surface of the tuber was examined for symptoms of PVY. Symptoms were noted as having external rings, which were normally located around the eyes of the tuber, necrotic in color, and could be raised or sunken. Other external defects were noted such as malformed in shape or skin defects such as rough skin or enlarged lenticels. Each tuber was cut into planks (6 cm x 1 cm x length of tuber) using a Vollrath potato cutter (The Vollrath Company, L.L.C., Sheboygan, WI) and inspected for internal symptoms, such as spots, rings/arcs (depending on the severity, some arcs made complete rings), or necrosis under the skin (Figure 2.1). These internal symptoms were necrotic in color and could range from one to many areas throughout the tuber. External rings were denoted as external while internal ring/arc, internal spot and necrosis under the skin were combined as internal.

The center plank from each tuber was fried in canola oil at 191 °C for 3.5 minutes. Pictures were taken on at least one replication of the raw and fried center plank from each tuber. Fry color was measured on the stem and bud end of each center tuber plank using a 577 Photovolt Reflection meter (model 577, Photovolt Instruments Inc., Minneapolis, MN). On the photovolt a green filter was calibrated using a black-cavity standard as 0.0% reflectance and a white plaque as 99.9% reflectance. A relationship between USDA fry color and photovolt reflectance as measured by our instrument and methodology was previously established. The relationship produced a scale of USDA fry color 1 to 4 (Table 2.1). Lower reflectance ratings indicate a darker fry color.

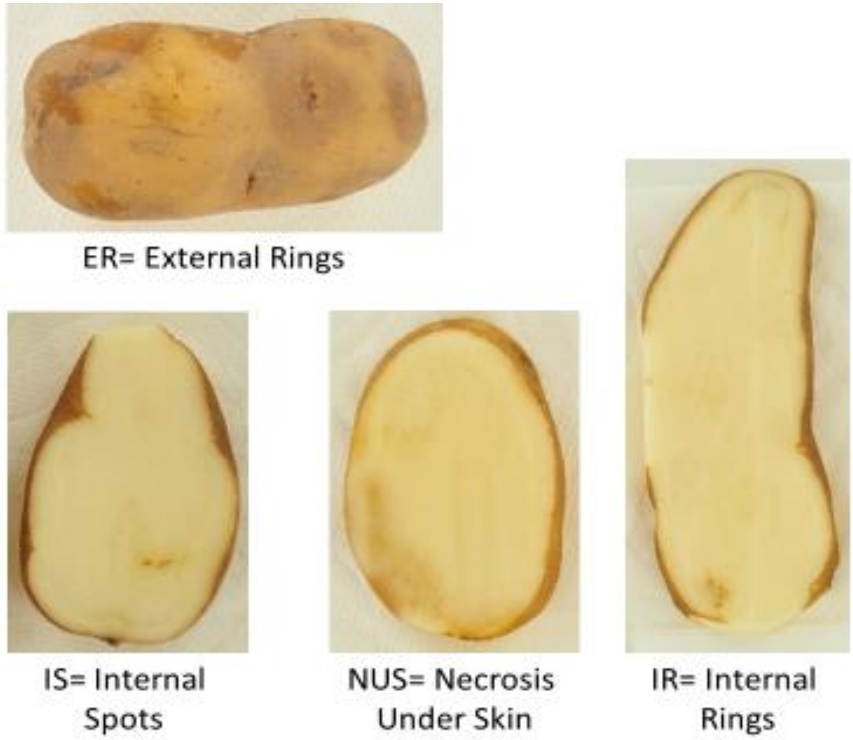

Figure 2.1: Photos of external and internal symptoms that were noted during evaluations

Table 2.1: Relationship between USDA fry number and reflectance ratings.

USDA Fry Color	Reflectance Reading
1	43.0 or greater
2	43.0 - 35.3
3	35.3 - 25.8
4	Less than 25.8

Mottling, sugar end, and any other defects that may show in the tuber after being fried were noted at the same time as fry color. The severity of mottling was noted using a 1 to 4 rating scale (Table 2.2). The presence of sugar ends was rated using a 0 or 1 scale, 1 being it had the presence of a sugar end and 0 being the absence of a sugar end. Planks were considered to have a sugar end if a predominant color of number 3 or darker, when compared to the USDA Munsell Color Chart for French Fried Potatoes, was seen on any 2 sides extending 1.3 cm or more from the end of the fried strip.

Table 2.2: Potato visual mottling rating scale for fried planks.

Visual Mottling Rating	Visual Observation
1	No mottling
2	Mild mottling (light colored, non-uniform surface browning not covering the entire fried plank)
3	Moderate mottling (light colored, non-uniform surface browning covering the entire fried plank)
4	Severe mottling (dark colored, non-uniform surface browning covering the entire fried plank)

The stem end peelings and the remaining tuber tissue were bagged in clear bags (15.2cm X 20.3cm, GLC'S Tapes Plus, Twin Falls, ID) that were pre-labeled with treatment, block, and plant number. Bagged samples were placed in a larger clear bag (50.8cm x 61cm, GLC'S Tapes Plus, Twin Falls, ID) and placed at 5.3° C until shipping. Bagged samples were placed in a Styrofoam cooler with ice packs to keep cool until the time of arrival and the Styrofoam cooler was placed in an insulated shipping box (48.3cm x 30.5cm x 31.75cm, Insulated Shipping Kits, ULINE). Samples were sent to A. Karasev in Moscow, Idaho, University of Idaho, for PVY testing and strain typing using ELISA and RT-PCR (Funke et al. 2017).

Statistics

Data were analyzed using the program SAS version 9.4 (SAS Institute Inc., Cary, NC). An analysis of variance was performed using Proc GLIMMIX code. Least-square means (LS means) tests for comparisons among variety, strain, time on each data variable (yield, tuber specific gravity, fry color, mottling, sugar ends, tuber infection incidence and tuber symptoms) were used. Means were considered significant at the $P \leq 0.05$ when the convergence criterion was satisfied.

Chapter 3: Results

Yield

Yield data was analyzed from plants positive for PVY compared to the healthy controls (Table 3.1). Yield data from both years were analyzed and convergence criterion satisfied. There was a significant difference between years (P=<0.0001), therefore yield data was analyzed by year. Plants in year one produced significantly lower tuber weight compared to year two (0.39 kg/plant vs. 0.83 kg/plant). Umatilla Russet had a significant higher yield per plant compared to Alturas, Russet Burbank and Ranger Russet. Russet Burbank and Ranger Russet had similar yields and Alturas had the lowest yield per plant. There was no significant difference in yield per plant among the PVY strains, and no interactions with variety or year.

Yield data from year one (Table 3.2) showed that variety has a significant effect (P= <0.0001). All varieties were statistically different from each other, with Umatilla Russet having the higher yield per plant compared to Russet Burbank, Ranger Russet, while Alturas had the lowest yield per plant. However, with the three PVY strains tested in this research, strain did not significantly impact yield. There was no interaction between strain and variety.

Yield data from year two (Table 3.3) also showed a significant variety effect (P= 0.0008). Umatilla Russet had significantly higher yield per plant compared to Alturas, Russet Burbank, and Ranger Russet, which had statistically comparable yields to each other. Current season infection with PVY did not influence yield, regardless of strain. There was no interaction between strain and variety.

Table 3.1: Yield for both years (2015 & 2016) of four varieties and three strains of PVY and a healthy control. Means are for weight (kg/plant). Values represented are LS means. Means followed by different letters are significantly different at α= 0.05.

Yield (kg/plant)					
Variety	**Healthy**	**NTN**	**N-Wi**	**O**	**Variety Mean**
Alturas	0.44	0.39	0.33	0.31	0.37 c
Russet Burbank	0.64	0.72	0.73	0.50	0.64 b
Ranger Russet	0.68	0.51	0.62	0.52	0.58 b
Umatilla Russet	0.88	0.80	0.77	0.90	0.84 a
P-Values					
Year	<0.0001	2015= 0.39 b, 2016= 0.83 a			
Variety	<0.0001				
Strain	0.4084				
Strain*Variety	0.5537				
Year*Variety	0.3825				
Year*Strain	0.9309				

Table 3.2: Yield for year one (2015) of four varieties and three strains of PVY and a healthy control. Means are for weight (kg/plant). Values represented are LS means. Values with the same letter indicate no significant difference at α= 0.05.

Yield (kg/plant)					
Variety	**Healthy**	**NTN**	**N-Wi**	**O**	**Variety Mean**
Alturas	0.09	0.10	0.13	0.12	0.11 d
Russet Burbank	0.47	0.50	0.55	0.40	0.48 b
Ranger Russet	0.41	0.32	0.44	0.33	0.37 c
Umatilla Russet	0.75	0.56	0.54	0.53	0.59 a
P-Values					
Variety	<0.0001				
Strain	0.2362				
Strain*Variety	0.4627				

Table 3.3: Yield for year two (2016) of four varieties and three strains of PVY and a healthy control. Means are for weight (kg/plant). Values represented are LS means. Values with the same letter indicate no significant difference at α= 0.05.

Yield (kg/plant)					
Variety	**Healthy**	**NTN**	**N-Wi**	**O**	**Variety Mean**
Alturas	0.79	0.67	0.54	0.51	0.63 b
Russet Burbank	0.80	0.93	0.90	0.61	0.81 b
Ranger Russet	0.95	0.71	0.81	0.72	0.80 b
Umatilla Russet	1.02	1.04	1.0	1.31	1.09 a
P-Values					
Variety	0.0008				
Strain	0.7769				
Strain*Variety	0.5183				

Tuber Specific Gravity

Tuber specific gravity data were analyzed from plants that were positive for PVY and compared to the healthy controls. Specific gravity data from both years (Table 3.4) were analyzed, convergence criterion was satisfied and there was a significant difference between years (P= 0.0016), therefore specific gravity data was also analyzed by year. Year one harvested tubers had significantly lower specific gravity per plant than year two (1.0575 versus 1.0647). Differences in specific gravity were also observed between varieties, with the higher specific gravity from Umatilla Russet and Russet Burbank tubers compared to Ranger Russet. Strain also had a significant effect, with tubers from PVY^{NTN} and $PVY^{N\text{-}Wi}$ infected plants having significantly higher specific gravity compared to healthy and PVY^{O} infected plants. There were no significant two way interactions.

Tuber specific gravity from year one (Table 3.5) showed no significant effect due to PVY strain and variety. There was also no interaction between strain and variety.

In year two (Table 3.6) both PVY strain (P= 0.0025) and variety (P= 0.0028) had a significant effect on specific gravity. Tubers of Umatilla Russet had significantly higher specific gravity compared to Alturas and Ranger Russet. Russet Burbank had statistically similar tuber specific gravity compared to Umatilla Russet and Alturas. Tubers with PVY^{NTN} and $PVY^{N\text{-}Wi}$ had statistically similar and significantly higher tuber specific gravity compared to the healthy control and PVY^{O}. Healthy tubers and tubers with PVY^{O} were statistically similar to each other. There was no interaction between strain and variety.

Table 3.4: Specific gravity for both years (2015 & 2016) of four varieties and three strains of PVY. Values represented are LS means. Values with the same letter indicate no significant difference at α= 0.05.

Specific gravity[1]					
Variety	**Healthy**	**NTN**	**N-Wi**	**O**	**Variety Mean**
Alturas	1.0602	1.0589	1.0649	1.0541	1.0595 bc
Russet Burbank	1.0599	1.0667	1.0688	1.0575	1.0632 ab
Ranger Russet	1.0530	1.0683	1.0637	1.0344	1.0549 c
Umatilla Russet	1.0644	1.0676	1.0687	1.0670	1.0669 a
Strain Mean	1.0594 b	1.0654 a	1.0665 a	1.0532 b	
P-Values					
Year	0.0016	2015= 1.0575 b,2016= 1.0647 a			
Variety	0.0020				
Strain	0.0005				
Strain*Variety	0.0906				
Year*Variety	0.3378				
Year*Strain	0.6338				

[1]Specific gravity measured at harvest by the weight in air, weight in water method.

Table 3.5: Specific gravity for year one (2015) of four varieties and three strains of PVY. Values represented are LS means. Values with the same letter indicate no significant difference at α= 0.05.

Specific gravity[1]				
Variety	**Healthy**	**NTN**	**N-Wi**	**O**
Alturas	1.0619	1.0549	1.0661	1.0501
Russet Burbank	1.0593	1.0607	1.0643	1.0481
Ranger Russet	1.0473	1.0593	1.0633	1.0400
Umatilla Russet	1.0596	1.0617	1.0621	1.0690
P-Values				
Variety	0.3971			
Strain	0.2573			
Strain*Variety	0.8282			

[1]Specific gravity measure at harvest by the weight in air, weight in water method.

Table 3.6: Specific gravity for year two (2016) of four varieties and three strains of PVY. Values represented are LS means Values with the same letter indicate no significant difference at α= 0.05.

Specific gravity[1]					
Variety	**Healthy**	**NTN**	**N-Wi**	**O**	**Variety Mean**
Alturas	1.0584	1.0616	1.0637	1.0619	1.0614 bc
Russet Burbank	1.0606	1.0728	1.0736	1.0647	1.0679 ab
Ranger Russet	1.0588	1.0758	1.0653	1.0340	1.0585 c
Umatilla Russet	1.0692	1.0738	1.0752	1.0688	1.0717 a
Strain Mean	1.0617 b	1.0710 a	1.0695 a	1.0573 b	
P-Values					
Variety	0.0028				
Strain	0.0025				
Strain*Variety	0.0569				

[1]Specific gravity measured at harvest by the weight in air, weight in water method.

Fry Color

Fry color data was analyzed using fry color measurements from tubers that were positive with PVY and compared to the healthy controls (Table 3.7). Fry color data from both years were analyzed, convergence criterion was satisfied and there was not a significant difference between years (P= 0.1932). PVY^{O} was not included in the analysis for both years due to year two producing too few positive tubers to be included. There was a significant effect of variety (P= <0.0001), strain (P=<0.0001), and time in storage (P=<0.0001); as well as interactions of strain by variety (P= 0.0279) and variety by time (P= 0.0112). There was no significant interaction between strain and time of evaluation (P= 0.9228).

Alturas had a significantly lighter fry color than the other three varieties, while Umatilla Russet had lighter fry color compared to Russet Burbank and Ranger Russet. Tubers from plants infected with PVY^{NTN} and $PVY^{N\text{-}Wi}$ had significantly lighter fry color compared to the healthy control. Fry color became significantly darker over time in storage, with the lightest fry color observed at harvest. There was a significant interaction between strain and variety (Table 3.8), which showed that the variety Alturas with the healthy control, PVY^{NTN} and $PVY^{N\text{-}Wi}$ and Umatilla Russet with PVY^{NTN} and $PVY^{N\text{-}Wi}$ had significantly lighter fry color compared to all other varieties and strains. Alturas did not respond to PVY infection by exhibiting a change in fry color, while the other three varieties did. There was also a significant interaction with variety and time (Table 3.9) which showed that the variety Alturas at harvest and mid-storage had significantly lighter fry color compared to the other three varieties throughout time in storage. Ranger Russet decreased in fry color reflectance more than the other three varieties.

To include PVY^{O} results in the analysis of fry color, data was analyzed by individual years.

There were significant effects on fry color in year one due to PVY strains (P= 0.0003), variety (P= 0.0001) and time of evaluation in storage (P= <0.0001) (Table 3.10). Alturas had significantly lighter fry color compared to Russet Burbank and Ranger Russet. Fry color from Umatilla Russet was statistically similar to Alturas and Russet Burbank. Tubers with PVY^{NTN} and $PVY^{N\text{-}Wi}$ infection had significantly lighter fry color compared to the healthy control and PVY^{O}. PVY^{NTN} and $PVY^{N\text{-}Wi}$ fry colors were statistically similar to each other. Healthy and PVY^{O} fry colors were statistically similar to each other and significantly darker than PVY^{NTN} and $PVY^{N\text{-}Wi}$.

Time of evaluation had a significant effect on fry color, and fries became darker over time in storage. Tubers from all varieties infected with the three PVY strains had acceptable fry color through all three evaluations, except Alturas with PVY^{O} had a reflectance rating of 30.7 at the final evaluation, which is a USDA 3 fry color (Table 3.11). Fry color differed with strain by variety (Table 3.11).

There were significant effects on fry color in year two due to PVY strain (P= 0.0001), variety (P= <0.0001), and time of evaluations (P= <0.0001) (Table 3.12). PVY^{O} was not included in this analysis due to the low number of positive tuber samples. Alturas tubers had a significantly lighter fry color compared to Russet Burbank, Ranger Russet and

Umatilla Russet. Russet Burbank and Ranger Russet fry colors were statistically similar to each other. Tubers infected with PVY^{NTN} and $PVY^{N\text{-}Wi}$ had significantly lighter fry color compared to the healthy control. Fry color became darker with time in storage, but remained within acceptable range.

There were no significant two way interactions nor was the three- way interaction (strain by variety by time) significant here or with any of the following parameters (mottling, sugar ends, tuber infection, and tuber symptoms).

Table 3.7: Fry color for both years (2015 & 2016) of four varieties and two strains of PVY and a healthy control. Tubers held at 8.9° C and evaluated at three different times throughout the storage season (harvest, 5 months and 10 months). Values represented are LS means. Fry color is measured in percent reflectance and is based on a scale of 0-100 with 100 being the lightest fry color. PVY strain O was not included in the analysis due to year two having a low number of positive samples. Values with the same letter indicate no significant difference at α= 0.05.

Fry color (% reflectance)			
HARVEST			
Variety	**Healthy**	**NTN**	**N-Wi**
Alturas	60.8	61.0	60.8
Russet Burbank	48.8	53.0	53.7
Ranger Russet	48.5	53.3	56.9
Umatilla Russet	49.5	56.8	57.5
MID-STORAGE			
Variety	**Healthy**	**NTN**	**N-Wi**
Alturas	58.0	57.3	58.7
Russet Burbank	44.8	53.4	51.3
Ranger Russet	42.8	48.0	50.1
Umatilla Russet	48.4	55.0	55.9
LATE-STORAGE			
Variety	**Healthy**	**NTN**	**N-Wi**
Alturas	52.7	55.5	49.5
Russet Burbank	39.3	49.1	47.4
Ranger Russet	36.3	39.7	44.6
Umatilla Russet	44.8	52.6	54.9
Strain Mean	47.9 b	52.9 a	53.4 a
P-Values			
Year	0.1932		
Variety	<.0001	Alturas= 57.1 a, RB[1]= 49.0 c, RR[1]= 46.7 c, UR[1]= 52.8 b	
Strain	<.0001		
Time	<.0001	Harvest= 55.0 a, Mid= 52.0 b, Late= 47.2 c	
Strain*Variety	0.0279		
Strain*Time	0.9228		
Variety*Time	0.0112		

[1]RB= Russet Burbank, RR= Ranger Russet and UR= Umatilla Russet

Table 3.8: Fry color for both years (2015 & 2016) of four varieties and two strains of PVY and a healthy control. LS means for variety and strain include all three evaluations throughout the storage season. Fry color is measured in percent reflectance and is based on a scale of 0-100 with 100 being the lightest fry color. Values with the same letter indicate no significant difference at α= 0.05.

Fry color (% reflectance)			
Variety	**Healthy**	**NTN**	**N-Wi**
Alturas	57.2 a	57.9 a	56.3 a
Russet Burbank	44.3 fg	51.9 bcd	50.8 cde
Ranger Russet	42.6 g	47.0 ef	50.5 de
Umatilla Russet	47.6 ef	54.8 abc	56.1 ab

Table 3.9: Fry color for both years (2015 & 2016) of four varieties and three evaluation times. Fry color is measured in percent reflectance and is based on a scale of 0-100 with 100 being the lightest fry color. Values represented are in LS means. Values with the same letter indicate no significant difference at α= 0.05.

Fry color (% reflectance)			
Variety	**Harvest**	**Mid-Storage**	**Late-Storage**
Alturas	60.9 a	58.0 ab	52.6 cd
Russet Burbank	51.8 cd	49.8 de	45.3 f
Ranger Russet	52.9 cd	47.0 ef	40.2 g
Umatilla Russet	54.6 bc	53.1 cd	50.8 d

Table 3.10: Fry color for year one (2015) of four varieties and three strains of PVY plus a healthy control. Tubers held at 8.9° C and evaluated at three different times throughout the storage season (harvest, 5 months and 10 months). Fry color is measured in percent reflectance and is based on a scale of 0-100 with 100 being the lightest fry color. Values represented are LS means. Values with the same letter indicate no significant difference at α= 0.05.

Fry color (% reflectance)				
HARVEST				
Variety	**Healthy**	**NTN**	**N-Wi**	**O**
Alturas	59.5	60.1	57.0	60.4
Russet Burbank	51.2	54.9	53.5	54.4
Ranger Russet	50.6	52.0	56.9	46.5
Umatilla Russet	46.2	58.4	55.8	57.2
MID-STORAGE				
Variety	**Healthy**	**NTN**	**N-Wi**	**O**
Alturas	60.3	59.0	59.9	53.7
Russet Burbank	47.6	55.4	53.0	53.6
Ranger Russet	46.6	51.4	54.1	44.7
Umatilla Russet	50.4	59.4	59.8	53.9
LATE-STORAGE				
Variety	**Healthy**	**NTN**	**N-Wi**	**O**
Alturas	49.4	55.9	42.3	30.7
Russet Burbank	40.8	48.6	46.7	44.8
Ranger Russet	36.8	39.5	42.4	38.1
Umatilla Russet	43.9	53.0	54.1	39.3
Strain Mean	48.6 b	54.0 a	53.0 a	48.1 b
P-Values				
Variety	0.0001	Alturas= 54.0 a, RB[1]= 50.4 b, RR[1]= 46.6 c, UR[1]= 52.6 ab		
Strain	0.0003			
Time	<.0001	Harvest= 54.7 a, Mid= 53.9 a, Late= 44.1 b		
Strain*Variety	0.0502			
Strain*Time	0.0588			
Variety*Time	0.0872			

[1]RB= Russet Burbank, RR= Ranger Russet and UR= Umatilla Russet

Table 3.11: Fry color for year one (2015) of four varieties and three strains of PVY and a healthy control. LS means for variety and strain include all three evaluations throughout the storage season. Fry color is measured in percent reflectance and is based on a scale of 0-100 with 100 being the lightest fry color. Values with the same letter indicate no significant difference at α= 0.05.

Fry color (% reflectance)				
Variety	**Healthy**	**NTN**	**N-Wi**	**O**
Alturas	56.4 abc	58.3 a	53.0 abcd	48.3 defg
Russet Burbank	46.5 efg	53.0 abcd	51.1 bcde	51.0 cde
Ranger Russet	44.7 fg	47.6 defg	51.1 bcde	43.1 g
Umatilla Russet	46.8 efg	56.9 ab	56.6 abc	50.1 def

Table 3.12: Fry color for year two (2016) of four varieties and two strains of PVY and a healthy control. Tubers held at 8.9° C and evaluated at three different times throughout the storage season (harvest, 5 months and 10 months). Values represented are LS means. PVY strain O was not included in the analysis due to year 2 having a low rate of positive samples. Fry color is measured in percent reflectance and is based on a scale of 0-100 with 100 being the lightest fry color. Values with the same letter indicate no significant difference at α= 0.05.

Fry color (% reflectance)			
HARVEST			
Variety	**Healthy**	**NTN**	**N-Wi**
Alturas	62.0	62.0	64.6
Russet Burbank	46.5	51.2	53.8
Ranger Russet	46.4	54.6	57.0
Umatilla Russet	52.8	55.2	59.1
MID-STORAGE			
Variety	**Healthy**	**NTN**	**N-Wi**
Alturas	55.8	55.6	57.5
Russet Burbank	41.9	49.5	49.6
Ranger Russet	39.1	43.0	46.1
Umatilla Russet	46.5	50.7	48.9
LATE-STORAGE			
Variety	**Healthy**	**NTN**	**N-Wi**
Alturas	56.0	55.4	56.8
Russet Burbank	38.0	50.2	47.6
Ranger Russet	35.8	40.0	46.8
Umatilla Russet	45.6	51.5	55.8
Strain Mean	47.2 b	51.6 a	53.6 a
P-Values			
Variety	<0.0001	Alturas= 58.4 a, RB[1]= 47.6 c, RR[1]= 45.4 c, UR[1]= 51.8 b	
Strain	0.0001		
Time	<.0001	Harvest= 55.4 a, Mid= 48.7 b, Late= 48.3 b	
Strain*Variety	0.3214		
Strain*Time	0.6848		
Variety*Time	0.0815		

[1]RB= Russet Burbank, RR= Ranger Russet and UR= Umatilla Russet

Mottling

Mottling data from tubers that were positive for PVY were compared to a healthy control. Mottling data from both years (Table 3.13) did not include data from PVY^{O} tubers, as there were too few to be included in the analysis. Mottling data met convergence criterion and there was not a significant effect of year (P= 0.3783), therefore, the data are presented as the means of two years. Variety, strain and time all had significant effects on mottling, while the interaction of variety by strain (P= 0.2355) and strain by time (P= 0.7026) were not significant.

Ranger Russet had statistically higher (P= <0.0001) mottling compared to the other three varieties, followed by Umatilla Russet, Russet Burbank and Alturas, which were all statistically different from each other. Healthy tubers had statistically (P= <0.0001) higher mottling than tubers with PVY^{NTN} or $PVY^{N\text{-}Wi}$. Tuber mottling was more severe in the late-storage evaluations as compared to the two earlier evaluations. The variety by time interaction showed Alturas and Ranger Russet severity of mottling increasing as the storage season progressed while mottling severity of Russet Burbank and Umatilla Russet remained similar at each evaluation.

Mottling data were also analyzed by individual years due to year two producing too few of PVY^{O} positive tuber to be included in the analysis.

In year one (Table 3.14) there were significant effects on mottling due to PVY strain (P=<0.0001), variety (P= <0.0001), and time of evaluation (P= <0.0001). There was also a significant interaction between strain and variety (P= 0.0066) and variety and time (P=

0.0008). Ranger Russet tubers had significantly higher mottling rating compared to Alturas, Russet Burbank, and Umatilla Russet. Mottling in tubers infected with PVY^{O} and the healthy control tubers were statistically similar and were higher compared to PVY^{NTN} and $PVY^{N\text{-}Wi}$. PVY^{NTN} and $PVY^{N\text{-}Wi}$ tubers were statistically similar in mottling to each other. By the late-storage evaluation there was a significantly higher amount of mottling compared to harvest and mid-storage. Table 3.15 shows the interaction between strain and variety and indicates Ranger Russet tubers with PVY^{O} had significantly higher level of mottling and Alturas with PVY^{NTN} had significantly lower level of mottling. Russet Burbank did not show a significant change in mottling when infected with PVY strains, while the other three varieties did.

In year two, (Table 3.16) there were significant effect of PVY strain ($P= <0.0001$), variety ($P= <0.0001$), and time of evaluation ($P= 0.0007$). There was also a significant interaction between variety and time ($P= 0.0137$). PVY^{O} was not included in this analysis due to a low number of positive tuber samples. Ranger Russet tubers had significantly higher amount of mottling compared to Alturas, Russet Burbank and Umatilla Russet. Russet Burbank and Alturas tubers showed statistically similar tuber mottling and were statistically lower than Umatilla Russet tubers. The tubers from the healthy control had a significantly higher amount of mottling compared to PVY^{NTN} and $PVY^{N\text{-}Wi}$ infected tubers. PVY^{NTN} and $PVY^{N\text{-}Wi}$ tubers were statistically similar in the amount of mottling. Mid-storage and late-storage had significantly higher amount of mottling compared to harvest. Mid and late storage were statistically similar in the amount of mottling. Ranger Russet in late-storage had significantly higher amount of mottling compared to Alturas, Russet Burbank, and Umatilla Russet, which were similar to each other.

Table 3.13: Mottling for both years (2015 & 2016) of four varieties and two strains of PVY and a healthy control. Tubers held at 8.9° C and evaluated at three different times throughout the storage season (harvest, 5 months and 10 months). Values represented are LS means. Mottling is a visual rating based on a scale of 1 to 4 with 4 being severe mottling and 1 being none. Mottling ratings performed on fried tuber sample. PVY strain O was not included in the analysis due to year two having a low rate of positive samples. Values with the same letter indicate no significant difference at α= 0.05.

Mottling (1 to 4 scale)				
HARVEST				
Variety	**Healthy**	**NTN**	**N-Wi**	**Variety Mean**
Alturas	1.3	1.1	1.0	1.1 g
Russet Burbank	1.6	1.3	1.3	1.4 ef
Ranger Russet	2.2	1.6	1.6	1.8 cd
Umatilla Russet	2.2	1.5	1.6	1.7 cd
MID-STORAGE				
Variety	**Healthy**	**NTN**	**N-Wi**	**Variety Mean**
Alturas	1.3	1.3	1.2	1.3 f
Russet Burbank	1.8	1.4	1.5	1.6 de
Ranger Russet	2.8	1.9	1.9	2.2 b
Umatilla Russet	2.5	1.7	1.9	2.0 bc
LATE-STORAGE				
Variety	**Healthy**	**NTN**	**N-Wi**	**Variety Mean**
Alturas	1.6	1.5	1.7	1.6 de
Russet Burbank	1.8	1.5	1.3	1.5 de
Ranger Russet	2.8	2.5	2.6	2.6 a
Umatilla Russet	2.1	1.6	1.5	1.7 cd
Strain Mean	1.9 a	1.5 b	1.5 b	
P-Values				
Year	0.3783			
Variety	<.0001	Alturas= 1.3 d, RB[1]= 1.5 c, RR[1]=2.2 a, UR[1]=1.8 b		
Strain	<.0001			
Time	<.0001	Harvest= 1.5 b, Mid= 1.7 a, Late= 1.8 a		
Strain*Variety	0.2355			
Strain*Time	0.7026			
Variety*Time	0.0003			

[1]RB= Russet Burbank, RR= Ranger Russet and UR= Umatilla Russet

Table 3.14: Mottling for year one (2015) of four varieties and three strains of PVY and a healthy control. Tubers held at 8.9° C and evaluated at three different times throughout the storage season (harvest, 5 months and 10 months). Values represented are LS means. Mottling is a visual rating based on a scale of 1 to 4 with 4 being severe mottling and 1 being none. Mottling ratings performed on fried tuber sample. Values with the same letter indicate no significant difference at α= 0.05.

Mottling (1 to 4 scale)					
HARVEST					
Variety	**Healthy**	**NTN**	**N-Wi**	**O**	**Variety Mean**
Alturas	1.2	1.0	1.0	1.0	1.0 f
Russet Burbank	1.5	1.1	1.2	1.3	1.3 e
Ranger Russet	2.1	1.7	1.5	2.2	1.8 bc
Umatilla Russet	2.5	1.6	1.8	1.7	1.9 bc
MID-STORAGE					
Variety	**Healthy**	**NTN**	**N-Wi**	**O**	**Variety Mean**
Alturas	1.1	1.0	1.2	1.9	1.3 e
Russet Burbank	1.8	1.4	1.6	1.4	1.5 d
Ranger Russet	3.1	2.3	1.9	3.2	2.6 a
Umatilla Russet	2.6	1.6	1.8	2.4	2.0 b
LATE-STORAGE					
Variety	**Healthy**	**NTN**	**N-Wi**	**O**	**Variety Mean**
Alturas	1.5	1.2	1.6	3.2	1.8 bcd
Russet Burbank	1.7	1.6	1.6	1.6	1.6 cd
Ranger Russet	2.8	2.5	2.7	3.1	2.7 a
Umatilla Russet	2.1	1.5	1.6	2.4	1.9 cb
Strain Mean	1.9 a	1.5 b	1.5 b	2.0 a	
P-Values					
Variety	<.0001	Alturas= 1.3 d, RB[1]= 1.5 c, RR[1]= 2.4 a, UR[1]= 1.9 b			
Strain	<.0001				
Time	<.0001	Harvest= 1.5 c, Mid= 1.8 b, Late= 2.0 a			
Strain*Variety	0.0066				
Strain*Time	0.0678				
Variety*Time	0.0008				

[1]RB= Russet Burbank, RR= Ranger Russet and UR= Umatilla Russet

Table 3.15: Mottling for year one (2015) of four varieties and three strains of PVY and a healthy control. Strain and variety for all three evaluations throughout the storage season. Mottling is a visual rating based on a scale of 1 to 4 with 4 being severe mottling and 1 being none. Mottling rating performed on fried tuber sample. Values with the same letter indicate no significant difference at α= 0.05.

Mottling (1 to 4 scale)				
Variety	**Healthy**	**NTN**	**N-Wi**	**O**
Alturas	1.3 ijk	1.1 k	1.2 jk	1.8 def
Russet Burbank	1.6 efgh	1.4 hij	1.4 ghi	1.4 ghij
Ranger Russet	2.6 ab	2.1 dc	2.0 cde	2.8 a
Umatilla Russet	2.4 abc	1.6 fgh	1.7 efg	2.2 bcd

Table 3.16: Mottling for year two (2016) of four varieties and two strains of PVY and a healthy control. Tubers held at 8.9° C and evaluated at three different times throughout the storage season (harvest, 5 months and 10 months). Values represented are LS means. Mottling is a visual rating based on a scale of 1 to 4 with 4 being severe mottling and 1 being none. Mottling ratings performed on fried tuber sample. PVY strain O was not included in the analysis due to year two having a low number of positive samples. Values with the same letter indicate no significant difference at α= 0.05.

Mottling (1 to 4 scale)				
HARVEST				
Variety	**Healthy**	**NTN**	**N-Wi**	**Variety Mean**
Alturas	1.3	1.3	1.0	1.2 e
Russet Burbank	1.8	1.5	1.3	1.5 d
Ranger Russet	2.3	1.5	1.6	1.8 bcd
Umatilla Russet	2.0	1.3	1.5	1.6 cd
MID-STORAGE				
Variety	**Healthy**	**NTN**	**N-Wi**	**Variety Mean**
Alturas	1.6	1.6	1.2	1.5 de
Russet Burbank	1.8	1.4	1.4	1.5 cd
Ranger Russet	2.5	1.4	1.9	1.9 bc
Umatilla Russet	2.3	1.8	2.0	2.0 b
LATE-STORAGE				
Variety	**Healthy**	**NTN**	**N-Wi**	**Variety Mean**
Alturas	1.7	1.6	1.7	1.7 bcd
Russet Burbank	2.0	1.3	1.2	1.5 de
Ranger Russet	2.8	2.6	2.5	2.6 a
Umatilla Russet	2.2	1.8	1.3	1.7 bcd
Strain Mean	2.0 a	1.6 b	1.5 b	
P-Values				
Variety	<.0001	Alturas= 1.4 c, RB[1]= 1.5 c, RR[1]= 2.1 a, UR[1]= 1.8 b		
Strain	<.0001			
Time	0.0007	Harvest= 1.5 b, Mid= 1.7 a, Late=1.8 a		
Strain*Variety	0.2616			
Strain*Time	0.9447			
Variety*Time	0.0137			

[1]RB= Russet Burbank, RR= Ranger Russet and UR= Umatilla Russet

Sugar Ends

Sugar end data were analyzed using sugar end ratings from tubers that were positive with PVY and compared to a healthy control. Sugar end data from both years (Table 3.17) were analyzed, convergence criterion was satisfied and there was a not a significant effect of years (P= 0.2792), time (P= 0.4974) or any two way interactions. There was a significant effect of variety on sugar end incidence, with Alturas having significantly lower incidence of this defect than the other three varieties, which were similar to each other. PVY strain was significantly different but all letters of significance were the same, most likely due to low power, and caution should be used in interpretation of significance.

Sugar end data were analyzed by individual years due to year two being low in PVY^O positive tuber samples and could not be included in the analysis.

In year one (Table 3.18) there was a significant effect of variety (P= 0.0019) on sugar end incidence, and an interaction between strain and variety (P= 0.0396). Umatilla Russet tubers had significantly higher incidence of sugar ends compared to Alturas, Russet Burbank, and Ranger Russet. Strain by variety (Table 3.19) was significant but all letters of significance were the same, most likely due to a low power and caution should be used in interpretation of significance. There were no significant differences with time or any time interactions.

PVY^O was not included in year two sugar end statistical analysis due to the low number of positive tuber samples. In year two, (Table 3.20) there was a significant effect of

PVY strain (P= 0.0398) on sugar end incidence, but all letters of significance were the same, most likely due to low power, and caution should be used in interpretation of significance.

Table 3.17: Sugar ends for both years (2015 & 2016) of four varieties and two strains of PVY and a healthy control. Tubers held at 8.9° C and evaluated at three different times throughout the storage season (harvest, 5 months and 10 months). Values represented are LS means. Sugar end ratings are a 0 or 1, with 0 being none and 1 being a sugar end. PVY strain O was not included in the analysis due to year two having a low rate of positive samples. Values with the same letter indicate no significant difference at α= 0.05.

Presence of sugar ends (0 to 1 scale)			
HARVEST			
Variety	**Healthy**	**NTN**	**N-Wi**
Alturas	0.08	0.09	0.0
Russet Burbank	0.54	0.27	0.36
Ranger Russet	0.38	0.44	0.26
Umatilla Russet	0.50	0.21	0.42
MID-STORAGE			
Variety	**Healthy**	**NTN**	**N-Wi**
Alturas	0.10	0.04	0.02
Russet Burbank	0.56	0.29	0.38
Ranger Russet	0.63	0.27	0.30
Umatilla Russet	0.51	0.37	0.32
LATE-STORAGE			
Variety	**Healthy**	**NTN**	**N-Wi**
Alturas	0.08	0.06	0.0
Russet Burbank	0.43	0.22	0.26
Ranger Russet	0.26	0.27	0.27
Umatilla Russet	0.60	0.12	0.19
Strain Mean	0.35 a	0.19 a	0.11 a
P-Values			
Year	0.2792		
Variety	0.0428	Alturas= 0.03 b, RB[1]= 0.36 a, RR[1]= 0.34 a, UR[1]= 0.34 a	
Strain	0.0008		
Time	0.4974		
Strain*Variety	0.4793		
Strain*Time	0.8782		
Variety*Time	0.9999		

[1]RB= Russet Burbank, RR= Ranger Russet and UR= Umatilla Russet

Table 3.18: Sugar ends for year one (2015) of four varieties and three strains of PVY and a healthy control. Tubers held at 8.9° C and evaluated at three different times throughout the storage season (harvest, 5 months and 10 months). Values represented are LS means. Sugar end ratings are a 0 or 1, with 1 being that there is a sugar end and 0 being none. Values with the same letter indicate no significant difference at α= 0.05.

Presence of sugar ends (0 to 1 scale)				
HARVEST				
Variety	**Healthy**	**NTN**	**N-Wi**	**O**
Alturas	0.08	0.04	0.00	0.00
Russet Burbank	0.29	0.12	0.50	0.17
Ranger Russet	0.33	0.46	0.14	0.53
Umatilla Russet	0.59	0.17	0.67	0.50
MID-STORAGE				
Variety	**Healthy**	**NTN**	**N-Wi**	**O**
Alturas	0.04	0.00	0.04	0.23
Russet Burbank	0.37	0.33	0.41	0.17
Ranger Russet	0.56	0.25	0.08	0.19
Umatilla Russet	0.61	0.25	0.37	0.63
LATE-STORAGE				
Variety	**Healthy**	**NTN**	**N-Wi**	**O**
Alturas	0.12	0.00	0.00	0.00
Russet Burbank	0.29	0.12	0.28	0.17
Ranger Russet	0.31	0.23	0.29	0.38
Umatilla Russet	0.67	0.12	0.29	0.64
P-Values				
Variety	0.0019	Alturas= 0.01 b, RB[1]= 0.25 b, RR[1]= 0.29 b, UR[1]= 0.44 a		
Strain	0.3486			
Time	0.8729			
Strain*Variety	0.0396			
Strain*Time	0.9893			
Variety*Time	0.8897			

[1]RB= Russet Burbank, RR= Ranger Russet and UR= Umatilla Russet

Table 3.19: Sugar ends for year one (2015) of four varieties and three strains of PVY and a healthy control. Variety by strain of all three evaluations throughout the storage season (harvest, 5 months and 10 months). Values with the same letter indicate no significant difference at α= 0.05.

Presence of sugar ends (0 to 1 scale)				
Variety	**Healthy**	**NTN**	**N-Wi**	**O**
Alturas	0.08 a	0.00 a	0.00 a	0.00 a
Russet Burbank	0.32 a	0.18 a	0.40 a	0.17 a
Ranger Russet	0.39 a	0.31 a	0.16 a	0.35 a
Umatilla Russet	0.62 a	0.17 a	0.44 a	0.59 a

Table 3.20: Sugar ends for year two (2016) of four varieties and two strains of PVY and a healthy control. Tubers held at 8.9° C and evaluated at three different times throughout the storage season (harvest, 5 months and 10 months). Values represented are LS means. Sugar end ratings are a 0 or 1, with 1 being that there is a sugar end and 0 being none. PVY strain O was not included in the analysis for year two due to having a low number of positive samples. Values with the same letter indicate no significant difference at α= 0.05.

Presence of sugar ends (0 to 1 scale)			
HARVEST			
Variety	**Healthy**	**NTN**	**N-Wi**
Alturas	0.08	0.13	0.00
Russet Burbank	0.80	0.42	0.22
Ranger Russet	0.42	0.42	0.38
Umatilla Russet	0.41	0.24	0.16
MID-STORAGE			
Variety	**Healthy**	**NTN**	**N-Wi**
Alturas	0.16	0.08	0.00
Russet Burbank	0.76	0.16	0.35
Ranger Russet	0.71	0.26	0.51
Umatilla Russet	0.41	0.50	0.23
LATE-STORAGE			
Variety	**Healthy**	**NTN**	**N-Wi**
Alturas	0.04	0.09	0.00
Russet Burbank	0.59	0.32	0.26
Ranger Russet	0.20	0.20	0.24
Umatilla Russet	0.55	0.10	0.08
Strain Mean	0.39 a	0.23 a	0.07 a
P-Values			
Variety	0.1002		
Strain	0.0398		
Time	0.8299		
Strain*Variety	0.2525		
Strain*Time	0.8908		
Variety*Time	0.9015		

Tuber Infection Incidence

The incidence of PVY infection was calculated by using the number of tubers that tested positive for PVY, divided by the total number of tubers harvested from PVY positive plants (tested at mid-season). Tubers from the healthy control were not included in the analysis because no infection was detected in tubers from healthy plants. Infection incidence for both years (Table 3.21) were analyzed, convergence criterion was satisfied and there was a significant difference between years (P= <0.0001). Therefore, infection incidence data was also analyzed by year.

Combined over both years, the main effect of PVY strain, and the strain by variety interaction were significant. However, variety, time and two way interactions were not significant, except for year by strain (P= <0.0001). Strain by variety (Table 3.22) was significant and indicates a difference among strains with the varieties. PVY^{NTN} tended to produce more infected tubers in Ranger Russet and Umatilla Russet but $PVY^{N\text{-}Wi}$ had the highest tuber infection in Alturas and Russet Burbank. Year by strain (Table 3.23) was significant (P= <0.0001) and showed PVY^{O} in year two had statistically lower level of tuber infection. Year one had a significantly higher infection incidence than year two (83 vs. 51%). There was a significantly lower infection incidence of PVY^{O} than the other strains.

In year one, (Table 3.24) PVY strain (P= 0.6626), variety (P= 0.5685), and time in storage (P=0.8150) had no significant effect on PVY infection incidence. There were no significant interactions between variables.

Infection incidence for year two (Table 3.25) also showed no significant differences among strain (P= 0.0568), varieties (P= 0.1281), time in storage (P=0.9791) or any interactions. However, a trend was observed in tuber disease infection with PVY^{O} being lower compared to the other strains except for Umatilla Russet in late-storage. Inferences can be made that there was a lower infection incidence in PVY^{O} tubers for all varieties when compared to PVY^{NTN} and $PVY^{N\text{-}Wi}$ tubers.

Table 3.21: Infection incidence of tubers of four varieties and three strains of PVY for both years (2015 & 2016). Tubers held at 8.9° C and evaluated at three different times throughout the storage season (harvest, 5 months and 10 months). Infection incidence measured in percent (%) of all tubers evaluated. Values represented are LS means. Values with the same letter indicate no significant difference at α= 0.05.

Infection incidence (%)			
HARVEST			
Variety	**NTN**	**N-Wi**	**O**
Alturas	98	100	41
Russet Burbank	78	88	40
Ranger Russet	67	75	45
Umatilla Russet	76	58	40
MID-STORAGE			
Variety	**NTN**	**N-Wi**	**O**
Alturas	95	98	47
Russet Burbank	38	57	46
Ranger Russet	71	50	28
Umatilla Russet	68	31	25
LATE-STORAGE			
Variety	**NTN**	**N-Wi**	**O**
Alturas	95	95	39
Russet Burbank	29	83	32
Ranger Russet	64	64	49
Umatilla Russet	61	60	61
Strain Mean	76 a	82 a	34 b
P-Values			
Year	<0.0001	2015= 82 a, 2016= 46 b	
Variety	0.0735		
Strain	<0.0001		
Time	0.4517		
Strain*Variety	0.0042		
Strain*Time	0.5385		
Variety*Time	0.4315		
Year*Strain	<0.0001		

Table 3.22: Infection Incidence of tubers of four varieties and three strains of PVY for both years. Variety by strain of all three evaluations throughout the storage season. Infection incidence measured in percent (%) of all tubers evaluated. Values with the same letter indicate no significant difference at α= 0.05.

Infection incidence (%)			
Variety	**NTN**	**N-Wi**	**O**
Alturas	96 a	99 a	38 ab
Russet Burbank	49 ab	76 a	33 b
Ranger Russet	67 a	62 a	33 b
Umatilla Russet	68 a	50 ab	32 b

Table 3.23: Infection Incidence of tubers of three strains of PVY for both years. Strain by year of all three evaluations throughout the storage season. Infection incidence measured in percent (%) of all tubers evaluated. Values with the same letter indicate no significant difference at α= 0.05.

Infection incidence (%)			
Year	**NTN**	**N-Wi**	**O**
Year one (2015)	85 a	84 ab	75 ab
Year two (2016)	64 b	80 ab	8 c

Table 3.24: Infection incidence of tubers of four varieties and three strains of PVY for year one (2015). Tubers held at 8.9° C and evaluated at three different times throughout the storage season (harvest, 5 months and 10 months). Infection incidence measured in percent (%) of all tubers evaluated. Values represented are LS means. Values with the same letter indicate no significant difference at α= 0.05.

Infection incidence (%)			
HARVEST			
Variety	**NTN**	**N-Wi**	**O**
Alturas	100	100	64
Russet Burbank	89	96	81
Ranger Russet	77	79	90
Umatilla Russet	85	75	81
MID-STORAGE			
Variety	**NTN**	**N-Wi**	**O**
Alturas	100	96	85
Russet Burbank	41	50	91
Ranger Russet	93	32	82
Umatilla Russet	89	41	48
LATE-STORAGE			
Variety	**NTN**	**N-Wi**	**O**
Alturas	92	93	73
Russet Burbank	36	100	66
Ranger Russet	73	64	86
Umatilla Russet	77	64	83
P-Values			
Variety	0.5685		
Strain	0.6626		
Time	0.8150		
Strain*Variety	0.3835		
Strain*Time	0.7052		
Variety*Time	0.9296		

Table 3.25: Infection incidence of tubers of four varieties and three strains of PVY for year two (2016). Tubers held at 8.9° C and evaluated at three different times throughout the storage season (harvest, 5 months and 10 months). Infection incident measured in percent (%) of all tubers evaluated. Values represented are LS means. Values with the same letter indicate no significant difference at α= 0.05.

Infection incidence (%)			
HARVEST			
Variety	**NTN**	**N-Wi**	**O**
Alturas	97	100	16
Russet Burbank	64	78	3
Ranger Russet	55	69	0
Umatilla Russet	64	40	0
MID-STORAGE			
Variety	**NTN**	**N-Wi**	**O**
Alturas	90	100	17
Russet Burbank	36	64	3
Ranger Russet	45	69	0
Umatilla Russet	43	22	0
LATE-STORAGE			
Variety	**NTN**	**N-Wi**	**O**
Alturas	97	97	12
Russet Burbank	23	65	3
Ranger Russet	54	64	0
Umatilla Russet	43	55	37
P-Values			
Variety	0.1281		
Strain	0.0568		
Time	0.9791		
Strain*Variety	0.2661		
Strain*Time	0.9870		
Variety*Time	0.9841		

Tuber Symptoms

Tuber symptom data were analyzed using the number of PVY positive tubers that visually showed a symptom out of the total number of PVY positive tubers. The healthy control was not included in the analysis because there was no cross contamination (from leaf and tuber testing) and the healthy plants did not produce any tubers with symptoms. Tuber symptoms for both years (Table 3.26) were analyzed, convergence criterion was satisfied and there were significant effects on the incidence of tuber symptoms due to PVY strain (P= <.0001). There were no significant effects due to year (P=0.4782), variety (P= 0.9317) or time in storage (P= 0.6598), and no significant two way interactions. Tuber symptoms included external rings, internal rings/arcs, internal spots, and necrosis under the skin. Overall, infection by PVY^{NTN} resulted in a higher percentage of tubers showing symptoms compared to PVY^{O} and $PVY^{N\text{-}Wi}$. The percent of tubers expressing symptoms did not significantly change with time in storage.

Even though year was not significant, due to the low number of PVY^{O} positive tubers in year two, data was analyzed by year.

In year one (2015), there was a significant effect of PVY strain (P= <.0001) on incidence of symptoms (Table 3.27). There was also a significant interaction of strain by variety (P= <.0001) and strain by time (P= 0.0300) (Table 3.28 & 3.29), while the main effects of variety and time were not significant. Tubers infected with PVY^{O} produced more symptoms compared to PVY^{NTN} and $PVY^{N\text{-}Wi}$. Symptoms continued to develop with time in storage, with the late storage evaluation showing a higher incidence in symptom development compare to harvest. This was primarily observed with tubers infected with PVY^{O}. Strain by variety was significantly different but all letters of significance were the same, most likely due to low power, and caution should be used in interpretation of significance. Inferences can be made indicating incidence of tuber symptoms was highest with PVY^{O} in all varieties except with Russet Burbank, where PVY^{NTN} had the highest incidence.

In year two (2016), there was a significant effect of PVY strain (P= 0.0099) on incidence of tuber symptoms (Table 3.30). $PVY^{N\text{-}Wi}$ infected tubers had a lower percent of symptom development compared to PVY^{NTN}. The number of PVY^{O} infected tubers in year two was too low to include in the analysis. Variety and time of evaluation did not significantly affect tuber symptoms in year two, and there were also no significant two way interactions.

There was a notable difference in the type of tuber symptoms observed among the four potato varieties and three PVY strains. For example, Russet Burbank only produced internal symptoms, regardless of PVY strain in both years. In contrast, both external and internal symptoms were observed with Ranger Russet with PVY^{NTN} and PVY^{O} in both years (Table 3.31 & 3.32).

Table 3.26: Tuber symptom incidence for both years (2015 & 2016) of four varieties and three strains of PVY. Tubers held at 8.9° C and evaluated at three different times throughout the storage season (harvest, 5 months and 10 months). Tuber symptoms are represented in percent (%). Values represented are LS means. Values with the same letter indicate no significant difference at α= 0.05.

Tuber symptom incidence (%)		
HARVEST		
Variety	**NTN**	**N-Wi**
Alturas	4	4
Russet Burbank	22	6
Ranger Russet	16	0.1
Umatilla Russet	12	3
MID-STORAGE		
Variety	**NTN**	**N-Wi**
Alturas	0.1	2
Russet Burbank	22	0.1
Ranger Russet	21	6
Umatilla Russet	12	0.1
LATE-STORAGE		
Variety	**NTN**	**N-Wi**
Alturas	18	24
Russet Burbank	13	2
Ranger Russet	22	0.1
Umatilla Russet	20	0.1
Strain Mean	12 b	2 c
P-Values		
Year	0.4782	
Variety	0.9317	
Strain	<0.0001	
Time	0.6598	
Strain*Variety	0.0722	
Strain*Time	0.8642	
Variety*Time	0.5324	

Table 3.27: Tuber symptom incidence for year one (2015) of four varieties and three strains of PVY. Tubers held at 8.9° C and evaluated at three different times throughout the storage season (harvest, 5 months and 10 months). Tuber symptoms are represented in percent (%). Values represented are LS means. Values with the same letter indicate no significant difference at α= 0.05.

Tuber symptom incidence (%)			
HARVEST			
Variety	**NTN**	**N-Wi**	**O**
Alturas	0.1	0.1	43
Russet Burbank	51	0.1	0.1
Ranger Russet	23	0.1	83
Umatilla Russet	19	0.1	12
MID-STORAGE			
Variety	**NTN**	**N-Wi**	**O**
Alturas	0.1	4	74
Russet Burbank	22	0.1	20
Ranger Russet	15	0.1	100
Umatilla Russet	7	0.1	59
LATE-STORAGE			
Variety	**NTN**	**N-Wi**	**O**
Alturas	25	41	69
Russet Burbank	30	0.1	17
Ranger Russet	25	0.1	100
Umatilla Russet	14	0.1	79
Strain Mean	15 b	0.1 b	63 a
P-Values			
Variety	0.6222		
Strain	<0.0001		
Time	0.0855		
Strain*Variety	<0.0001		
Strain*Time	0.0300		
Variety*Time	0.9042		

Table 3.28: Tuber symptom incidence for year one (2015) of four varieties and three strains of PVY. Data combined over all time evaluations. Values with the same letter indicate no significant difference at α= 0.05.

Tuber symptom incidence (%)			
Variety	**NTN**	**N-Wi**	**O**
Alturas	5 a	12 a	70 a
Russet Burbank	34 a	0.1 a	9 a
Ranger Russet	21 a	0.1 a	97 a
Umatilla Russet	12 a	0.1 a	49 a

Table 3.29: Tuber symptom incidence for year one (2015) of three strains of PVY and three different storage evaluations. Values with the same letter indicate no significant difference at α= 0.05.

Tuber symptom incidence (%)			
Strain	**Harvest**	**Mid-Storage**	**Late-Storage**
NTN	20 b	8 b	23 b
N-Wi	0.01 b	0.2 b	0.9 b
O	26 b	76 a	82 a

Table 3.30: Tuber symptom incidence for year two (2016) of four varieties and three strains of PVY. Tubers held at 8.9° C and evaluated at three different time throughout the storage season (harvest, 5 months and 10 months). Tuber symptoms are represented in percent (%). Values represented are LS means. Values with the same letter indicate no significant difference at α= 0.05.

Tuber symptom incidence (%)		
HARVEST		
Variety	**NTN**	**N-Wi**
Alturas	10	0.1
Russet Burbank	0.1	10
Ranger Russet	7	0.1
Umatilla Russet	3	7
MID-STORAGE		
Variety	**NTN**	**N-Wi**
Alturas	0.1	0.1
Russet Burbank	23	0.1
Ranger Russet	32	10
Umatilla Russet	20	0.1
LATE-STORAGE		
Variety	**NTN**	**N-Wi**
Alturas	12	7
Russet Burbank	0.1	3
Ranger Russet	15	0.1
Umatilla Russet	26	0.1
Strain Mean	7 a	2 b
P-Values		
Variety	0.7335	
Strain	0.0099	
Time	0.8721	
Strain*Variety	0.6019	
Strain*Time	0.2731	
Variety*Time	0.7015	

Table 3.31: Year one (2015) type (external or internal) and percent of tuber symptoms that were noted during evaluations at harvest, mid (5 months), and late (10 months) storage season. Symptoms noted were from positive tubers.

Variety	**NTN**			**N-Wi**			**O**		
	Harvest	**Mid**	**Late**	**Harvest**	**Mid**	**Late**	**Harvest**	**Mid**	**Late**
Alturas	None	None	Internal 25%	None	External/ Internal 4%	Internal 41%	External/ Internal 43%	External/ Internal 74%	Internal 69%
RB[1]	Internal 51%	Internal 22%	Internal 30%	None	None	None	None	Internal 20%	Internal 17%
Ranger[1]	External 23%	External/ Internal 15%	External/ Internal 25%	None	None	None	External/ Internal 83%	External/ Internal 100%	External/ Internal 100%
Umatilla[1]	External/ Internal 19%	Internal 7%	Internal 14%	None	None	None	Internal 12%	External 59%	External/ Internal 79%

[1]RB= Russet Burbank, Ranger= Ranger Russet and Umatilla= Umatilla Russet

Table 3.32: Year two (2016) type (external or internal) and percent of tuber symptoms that were noted during evaluations at harvest, mid (5 months), and late (10 months) storage season. Symptoms noted were from positive (+) tubers only.

Variety	**NTN**			**N-Wi**			**O**		
	Harvest	**Mid**	**Late**	**Harvest**	**Mid**	**Late**	**Harvest**	**Mid**	**Late**
Alturas	Internal 10%	None	External/ Internal 12%	None	None	Internal 7%	None	None	None
RB[1]	None	Internal 23%	None	Internal 10%	None	Internal 3%	None	None	None
Ranger[1]	External/ Internal 7%	External/ Internal 32%	External/ Internal 15%	None	External 10%	None	None	No + Tubers	No + Tubers
Umatilla[1]	Internal 3%	Internal 20%	External/ Internal 26%	Internal 7%	None	None	None	No + Tubers	No + Tubers

[1]RB= Russet Burbank, Ranger= Ranger Russet and Umatilla= Umatilla Russet

Chapter 4: Discussion

The varieties Alturas, Russet Burbank, Ranger Russet, and Umatilla Russet were selected because they are commonly grown for processing in the PNW. The potato industry strives for the highest yield and best quality crop possible. Quality usually refers to tuber starch content (dry matter and specific gravity), texture, reducing sugar content, fry color, and size and shape (Iritani 1981). Quality also includes minimizing tuber defects such as bruise or tuber necrotic symptoms of PVY (PTNRD).

An influential factor in tuber quality is stress upon a plant during the growth process. Common forms of plant stress affecting tubers are high and low temperature, high and low soil moisture, fertility imbalances, insects, viruses and other plant diseases. Stresses earlier in the growing season are likely to be more detrimental to potato quality than late-occurring stresses (Iritani 1981). The stress of infection or the direct impact of PVY on tuber yield and quality can vary by timing of infection, variety and environmental conditions. Tuber physiology changes with time in storage and may impact the tuber response to PVY infection and further altering quality.

The results from this study appear to be influenced by the growing conditions between years. Year was significant for most parameters measured and year one can be characterized by higher levels of stress when compared to year two. A potential stress may have been environmental conditions. Tuber yield and specific gravity were significantly lower in year one compared to year two and this may have been caused by different temperatures between the two years (Haynes et al. 1989; Rykaczewska 2015). Year one

(2015) had higher temperatures for a longer duration compared to year two (2016). The air temperature in year one (2015) was over 37° C for 13 consecutive days from June 26 to July 8 (USBR 2017). Over the entire growing season in year one there were 19 days at 37° C or above. In comparison, year two (2016) had only two occasions in which two consecutive days were 37° C and only four total days at 37° C or above. Although the growing degree days were similar among the two years, (2745 and 2783, respectively), year one had periods of higher temperatures, but also a 20 day shorter growing season. Therefore, the longer duration of extreme temperatures in year one may have been an additional stress to cause a yield and quality difference between years.

Additional stresses that may have contributed to differences between years in yield and quality were the potential for greater soil compaction and decrease in plant health. During the inoculation and sampling processes there may have been additional physical stresses to the plant in year one compared to year two. In year one, the layout of the screen house (Figure A.1) made walking through the rows difficult when inoculating and sampling, which may have physically damaged the plants. In year two, the layout (Figure A.2) provided additional space between rows making it easier to walk through and fewer plants were disturbed and appeared to be in better overall stature. There may also have been extra soil compaction in the tuber growing area from the inoculation and sampling process. Physical damage to the plant and soil compaction can impact yield and quality (Stalham et al. 2007) as seen with this study.

It is known that yield and specific gravity are variety dependent characteristics (Love et al. 2003b), and differences among the four varieties in this study were also observed. In general, Umatilla Russet had higher yield compared to Russet Burbank and Ranger Russet. Alturas had the lowest yields, but this variety is considered a late-season variety and production may have been limited in this study with a shorter growing season. Yields and specific gravity were lower in the screen-house produced tubers in both years compared to common yields seen in commercial fields in the area. Decreased screen-house yields and tuber specific gravity could be due to the soil compaction from repeated years of potato production. The permanent construction of the screen-house limits the size of tillage equipment used and prevents deep tillage. Compaction may also cause a general high prevalence of sugar ends (Olsen et al. 2003) as was observed in the study.

Interestingly, infection with PVY, regardless of strain did not significantly affect tuber yield. This suggests that in-season PVY infection may not have a significant impact on yield. This result is similar to previous research that has shown no impact on yield with in-season PVY infection in Russet Norkotah (Whitworth et al. 2010) but contradictory to Gibson (1991) that showed that infection with younger plants (1-4 weeks after emergence) leads to a greater reduction in yield than in older plants. Younger plants have less resistance and more time to translocate the virus to other tubers in the plant during the growing season. Inoculation in the screen-house was 5-6 weeks after planting. Emergence ratings were not taken but this timing would be considered early in the growing season and it is unknown if another timing would influence yield with the varieties used in this study.

One outcome from the associated potential stresses between years was the difference in plant and tuber infection with PVY^{O}. There is a trend for fewer plants to be infected with PVY^{O} in year two compared to year one (Funke 2017) for all cultivars but

Russet Burbank. This was interpreted as an expression of partial strain-specific resistance against PVY^{O}, however, infection in Russet Burbank remained high in both years. Past research has shown that there is higher efficiency of a hypersensitive resistance to PVY infection at lower temperatures (Choi et al. 2017). The less stressful temperature in year two may also explain the lower tuber infection.

There was significantly lower PVY^{O} tuber infection incidence in year two (8%) compared to year one (75%). This dramatic difference between years may be due to impact of environmental stress on virus translocation to tubers. There was also a significantly lower tuber incidence of PVY^{NTN} infection in year two versus year one, although infection was similar with $PVY^{N\text{-}Wi}$ between the years. These results indicate a potential difference in strain translocation to tubers as affected by environmental stresses. Past research has shown that PVY^{N} will translocate faster through the plant into the progeny tubers compared to PVY^{O} (Dupuis 2016). This may explain the difference in the level of tuber infection for PVY^{NTN} and $PVY^{N\text{-}Wi}$ compared to PVY^{O}. Even though Dupuis stated that $PVY^{N\text{-}Wi}$ is more efficient in translocation, this was not observed in this study where tuber infection rate of PVY^{NTN} and $PVY^{N\text{-}Wi}$ were similar among varieties. Alturas tubers reacted similarly with all strains. Russet Burbank tubers infected with $PVY^{N\text{-}Wi}$ had a higher tuber infection compared to PVY^{NTN} and PVY^{O}. Ranger Russet tubers infected with PVY^{O} were significantly lower in infection incidence compared to PVY^{NTN} and $PVY^{N\text{-}Wi}$. Umatilla Russet tubers infected with PVY^{NTN} had a greater infection incidence compared to PVY^{O}. There were distinct differences among varieties with tuber infection incidence, but the interaction with different strains suggests greater infection with PVY^{NTN} compared to PVY^{O} in Ranger Russet and Umatilla Russet. Alturas and Russet Burbank responded similarly between PVY^{NTN} and PVY^{O}. The data from Ranger Russet and Umatilla Russet agrees with past research that PVY^{N} movement throughout the plant and tubers is faster than PVY^{O} (Beemster 1976) whereas, Alturas and Russet Burbank having similar tuber infection rates did not. It is apparent there are significant interactions between variety and PVY strain infection. Therefore, it is likely that risk of tuber infection will be impacted by season, variety and PVY strain.

The data from this research also support the notion that growing conditions may play a role in tuber symptom development. PVY^{O} in year one had the higher incidence of tuber symptoms when compared to PVY^{NTN} and $PVY^{N\text{-}Wi}$. Normally PTNRD is associated with PVY^{NTN} (Karasev et al. 2008), and this was seen with this research except in a more stressful year (2015) when PVY^{O} showed the greatest level of PTNRD. Data from this research suggests some risk of PTNRD development with $PVY^{N\text{-}Wi}$ in a stressful year with the variety Alturas and in a milder year there is a low risk of PTNRD with the varieties Russet Burbank, Ranger Russet and Umatilla Russet. Although due to low power in the statistical analysis strain by variety could not be validated. Similarly to tuber infection, there were extreme differences in incidence of symptom development with PVY^{O} infected Russet Burbank tubers (9%) compared to the other three varieties (49 to 97%). Again, this suggests that Russet Burbank does not have hypersensitivity compared to these other varieties, even in a stressful year (Funke 2017).

The type of symptoms identified in PVY positive tubers were external rings, internal rings or arcs, internal spot and necrosis under the skin. When tubers were positive for PVY and showed one of the mentioned symptoms it was referred to as symptomatic. When a tuber that was positive with PVY and did not show any symptoms it was referred to as asymptomatic. There were numerous asymptomatic tubers present with PVY^{NTN} and PVY^{N-Wi} and in a milder year there were also asymptomatic tubers with PVY^{O}. Symptoms that were present varied with potato variety and PVY strain. Alturas tubers with PVY^{O} tended to show external and internal symptoms, Russet Burbank and Umatilla Russet tubers tended to show internal symptoms among all PVY strains and Ranger Russet tended to show external and internal symptoms with all PVY strains. Since PVY infected tubers may have limited visual symptoms it is of great importance to have a seed certification program in place to help limit the virus infection. Tuber sampling of some type could be of importance to help limit the presence of PVY infection in seed.

One of the objectives of this study was to see if there is a fry quality issue associated with PVY infection. Fry color is variety dependent (Stark and Love 2003). Alturas tended to have a lighter fry color when compared to Russet Burbank, Ranger Russet and Umatilla Russet. Although there was a significant difference in fry color among PVY strains interestingly, PVY^{NTN} and PVY^{N-Wi} had significantly lighter fry colors when compared to PVY^{O} and the healthy control. This means that fry color was not adversely affected by PVY infection. However, raw tuber symptoms were also seen after being fried. In the presence of symptoms, darkening of the fry around the symptom could be observed. Since reflectance values are only measured on the bud and stem end, color variation over the entire fry was not always recorded. This darker color associated with tuber symptoms would contribute to a decline in processing quality due to variable internal discoloration and not necessarily an overall impact on fry color. There was no detrimental impact on fry color with PVY recombinant strain infection except in the presence of a necrotic symptom in this study and, in some cases, it might have been a benefit to fry color.

Other characteristics of fry quality are specific gravity, mottling and sugar ends. PVY^{O} and the healthy control had lower specific gravity compared to PVY^{NTN} and $PVY^{N\text{-}Wi}$. Sugar ends, which is known to be a stress induced response, showed a trend for higher incidence in the healthy control tubers compared to PVY^{NTN} and $PVY^{N\text{-}Wi}$ strains. PVY^{NTN} and $PVY^{N\text{-}Wi}$ both years had significantly higher tuber specific gravity, lighter fry color, less mottling, and fewer sugar ends when compared to PVY^{O} and the healthy control. One possible reason for this response is the plant may have had a positive response to PVY^{NTN} and $PVY^{N\text{-}Wi}$. This has been seen before with herbicide sprays where foliage of the plant is negatively impacted but the crop may have an overall positive impact from it. One example is 2, 4-D, which is sometimes used as a growth regulator in plants (Munro et al. 1992). Examples of 2, 4-D having a positive plant response include the growth of favorable sized potatoes and enhanced color of the potatoes. The plants infected with PVY^{NTN} and $PVY^{N\text{-}Wi}$ may have responded positively, internalizing less stress and producing tubers with better fry quality. Further investigation is needed to see why these two strains respond in this way. These results show a concern with PVY^{NTN} and $PVY^{N\text{-}Wi}$ having tuber symptoms but less than a 15% chance that processing quality would be affected due to internal defect. The difference between PVY^{NTN}, $PVY^{N\text{-}Wi}$ and the healthy control might be in part due to the maturity of the tubers going into storage. Plant infection with PVY^{NTN} and $PVY^{N\text{-}Wi}$ could potentially induce a positive plant response that lead to longer plant health than the healthy control and PVY^{O} plants. Unfortunately, senescence ratings were not taken and this cannot be confirmed. Although there was an unusual response to PVY^{NTN} and $PVY^{N\text{-}Wi}$ in fry quality, there was only a slight chance of tuber symptom development.

The PNW stores most of their potatoes and a majority of them are used for processing. Processed potatoes tend to be stored at 8 to 9° C, and this temperature represents a compromise that limits the negative effects of higher temperatures on increased weight loss, disease pressure, and sprouting while at the same time minimizing cold-induced sweetening and the deterioration of processing quality (Driskill et al. 2007). Therefore, the effect of storage on PVY infected tubers is of great importance.

The incidence of tuber infection regardless of strain did not increase with time in storage. These results suggest the opportunity to test seed lots for the presence of PVY is early in the storage season to approximate infection incidence at planting. Time in storage also did not significantly impact incidence of tuber symptoms unless PVY^{O} was present, then symptoms increased by mid and late-storage evaluations. There also appears to be an increase in symptom development with PVY^{NTN} and $PVY^{N\text{-}Wi}$ infection with Alturas if potatoes are stored long term. This suggests that Alturas fields with these two strains may be at higher risk for symptoms development with time in storage. It also appears that the symptoms with PVY^{NTN} and $PVY^{N\text{-}Wi}$ present at harvest do not change in storage with Russet Burbank, Ranger Russet and Umatilla Russet.

In general, fry color darkened and mottling increased with time in storage. This is a consistent response seen in previous research and in the industry (Brandt et al. 2003;

Brandt et al. 2006; Woodell et al. 2004). All varieties had a deteriorated fry quality with time in storage but in particular, this was observed in Ranger Russet. Ranger Russet responded with darker fry colors with time in storage, which is normal for that variety and therefore it is not generally stored long term (Woodell et al. 2004). PVY strain did not influence fry color and tubers infected with all strains darkened with time in storage. Symptom development in storage is variety and strain dependent, but at harvest infection detection can provide insight on whether there is a greater risk for symptom development.

All varieties had an increase in mottling with time in storage except Umatilla Russet. The potential for mottling increases with time in storage and is of a greater concern with Ranger Russet and long term storage. Sugar ends is a physiological disorder associated with high soil temperature or soil moisture deficit at tuber initiation and early tuber bulking stages (Olsen et al. 2003). Compaction can also increase the presence of sugar ends. In this study, time in storage did not impact or change the presence of sugar ends. This corresponds with previous data showing sugar ends are present at harvest and won't increase with time in storage (Iritani et al. 1973).

There was a limited response with fry quality with time in storage, except if tubers were infected with PVY^{O}. The response with PVY^{NTN} and $PVY^{N\text{-}Wi}$ mimicked a healthy crop in storage. There appeared to be some impact on tuber symptom development with specific varieties but additional research needs to be directed at this response. With the apparent differences between years' additional research is needed to evaluate which environmental conditions may play a role.

Chapter 5: Conclusions

The objective of this research was to provide information for growers who experience in-season PVY infection in what to expect from processing quality and concerns with storing the crop. One of the main points that can be gleaned from this study was that the level of PVY tuber infection present at harvest will remain throughout storage. This also applies to the level of tuber symptoms except if dealing with PVY^{O}, which increased with time or the variety Alturas infected with PVY^{NTN} or $PVY^{N\text{-}Wi}$ which also increased with time in storage. Each variety used in the industry must be evaluated for a reaction to the various PVY strains since they will differ in their response.

This research also showed that not all tubers with PVY infection will show symptoms. This means that even though PVY is present, the tuber may look and act as a healthy tuber. Sometimes tubers showed a positive response to PVY^{NTN} and $PVY^{N\text{-}Wi}$ infection resulting in better overall fry quality than in healthy tubers. There is little concern with asymptomatic tubers infected with the recombinant strains during in-season infection to have any processing quality issues. The greatest concern with processing quality is due to the presence of symptoms that would be considered an internal defect. One factor that now needs to be actively included in the discussion of the risk in symptom development is the environmental conditions and overall crop health. Environmental stresses appeared to influence strain response among varieties as seen with an increase in tuber incidence and symptoms with PVY^{O} in a higher stress year. These responses are with in-season PVY infection and should not be related to seed-borne infection. These results point out the need for further research to evaluate how to keep a PVY infected field as healthy as possible to potentially overcome the impact of PVY infection and symptom development.

Knowing the variety, environmental conditions, and strain of PVY will aid in making decisions on what to do with the crop post-harvest. Results from this research will help identify the potential risk of a specific variety having tuber quality degradation if infected with a specific PVY strain.

Further research is needed to evaluate seed-borne PVY infection in different process varieties, in addition to those evaluated in this study, to see how it may impact yield and fry quality with time in storage. Additional research with both in-season and seed-borne PVY infection will lead to greater information available for growers to help plan ahead and continue the high quality standard of potatoes in the PNW.

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Appendix

Table A.1. Fertility program for the screen house in Oregon State University in Hermiston in 2015. Data was not obtained for 2016.

2015 Screen house Fertility		
Date	**Product Name**	**Rate**
May 22nd	Nitro (32-0-0-6)	9.3 L/37.4 L H_2O/hectare
June 4th	Nitro (32-0-0-6)	9.3 L/37.4 L H_2O/hectare
June 12th	Nitro (32-0-0-6)	18.7 L/74.8 L H_2O/hectare
June 19th	Nitro (32-0-0-6)	18.7 L/74.8 L H_2O/hectare
July 3rd	Nitro (32-0-0-6)	18.7 L/74.8 L H_2O/hectare

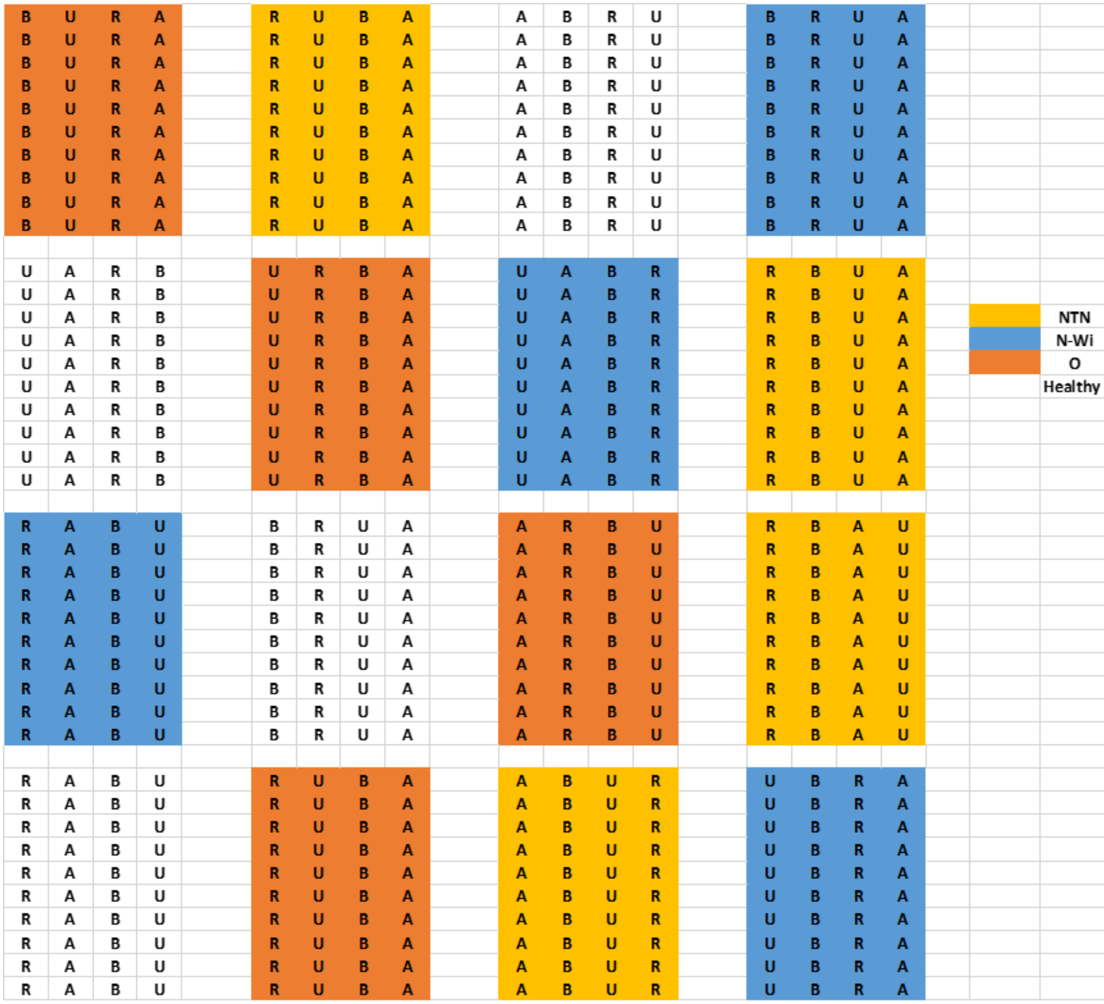

Figure A.1. Year one (2015) screen-house layout.

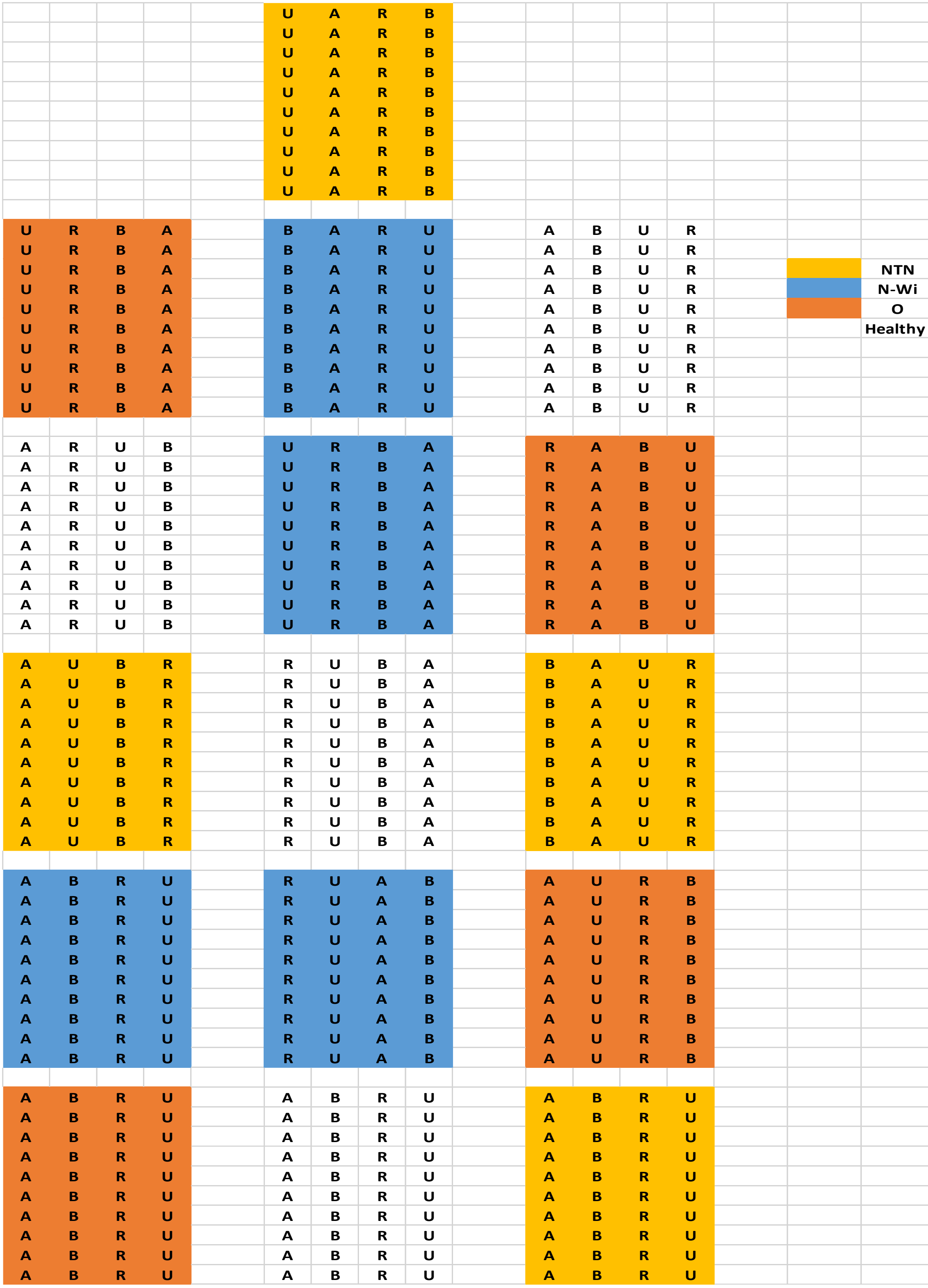

Figure A.2. Year two (2016) screen-house layout.