ABSTRACT

AKULA, ANIRUDH. Development, Field Evaluation and Economic Impact Assessment of a Mechanical Aid for Harvesting Sweetpotatoes. (Under the direction of Dr. Michael Boyette).

With the increase in demand for quality sweetpotatoes and the ever-increasing farm labor costs, the sweetpotato industry is investigating the use of mechanical harvesting as a possibility in the near future. Harvesting of sweetpotatoes involves separation of the vine material produced by the sweetpotato plants from the storage roots. It is beneficial to remove the vine material prior to harvesting to improve the harvesting efficiency, control root growth and decrease the damage to the roots during harvest. Researchers have made several attempts over the last 60 years to build a machine that achieves complete vine-root separation, but success has been elusive. As a result, a robust harvesting aid machine to detach the vines and the main stem from the sweetpotato roots below the soil was designed and developed to achieve complete vine-root separation prior to harvesting. Field testing of the vine puller-chopper harvesting aid involved a wide range of field conditions and varieties including Beauregard, Covington, Bellevue, Averre, and Jewel. The machine performance was evaluated in terms of separation efficiency for ground speeds up to 3 mph and the results obtained were consistent with those in literature with average separation efficiencies over 60% irrespective of crop variety, field or machine settings.

Many researchers have hypothesized that vine removal prior to harvesting is beneficial for toughening the sweetpotato root skin and reducing the damage to the roots during harvest and post-harvest handling, however, none of them have extensively quantified the effect yet. The effect of vine-root separation by the developed harvesting aid as a pre-harvest operation on the skin strength of the sweetpotato roots over time was studied. Three fields each of Beauregard and Covington varieties were evaluated. A modified version of the Halderson Periderm Shear Tester and Torquometer was used for measuring the skin torsion and normal load required to tear the

sweetpotato root skin surface. This was done for roots with their vines removed by the harvesting aid as well as for the roots with their vines intact as a measure of skin strength over a 16-day period. There was an overall increase in the observed skin torsion and normal load values for both the varieties when the harvesting aid was used compared to when it was not used. The quantification of skin strength over time can provide very useful information for growers and the equipment manufacturers to reduce damage to the roots during harvesting and post-harvest handling.

A simple economic study of the current harvesting scenarios involving the developed harvesting aid was conducted. Current harvesting practices in North Carolina include the roots being turned over by a disc plow or a chain digger and hand-collected for fresh market use, or the roots being dug using an available commercial mechanical digger for the processing industry. Harvesting scenarios were studied using the developed vine puller-chopper harvesting aid as a pre-harvest operation in terms of harvesting efficiency, time required to harvest, the labor required, the level of drudgery involved in terms of number of instances the farm crew had to reach out to separate the vines from the roots, along with the associated partial machine and labor costs. The harvesting aid emerged as a feasible and better alternative to the current pre-harvest mowing operation for both fresh market and processing roots. The current harvesting practice of using a disc plow as a mechanical aid, with no pre-harvest vine removal operations, was deemed to be the most economical with the available technology. However, there is potential for the vine puller-chopper harvesting aid to be involved in a future harvesting scenario to economically compete with the current disc plow harvesting practice.

Development, Field Evaluation and Economic Impact Assessment of a Mechanical Aid for Harvesting Sweetpotatoes

by
Anirudh Akula

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APPROVED BY:

Dr. Michael Boyette Committee Chair	Dr. Grant Ellington
Dr. Jason Osborne	Dr. Jonathan Schultheis

DEDICATION

To my father and grandmother, who could not be here with me...

To my mother and brother who have always been there for me!

BIOGRAPHY

Anirudh Akula was born in Hyderabad, India in the year 1990. He grew up in the city where most of his family still reside. He attended the Hyderabad Public School Begumpet from 1999 to 2006 for his middle school and part of his high school studies.

Anirudh went on to pursue Agricultural Engineering in 2009 for his undergraduate studies at the Indian Institute of Technology Kharagpur after making the top 1% of the country. As an undergrad he had the opportunity of working at Pennsylvania State University as a research intern during the summer of 2012 with Dr. Paul Heinemann and Dr. Jude Liu.

After his thoroughly enjoyable research experience at Penn State, he went on to complete his bachelor’s degree and moved to Raleigh, North Carolina in 2013 to continue his academic career and obtain a Doctor of Philosophy in Biological and Agricultural Engineering at North Carolina State University under the direction of Dr. Michael Boyette. Upon completion of his PhD, Anirudh intends to work in the industry.

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CHAPTER 1: Introduction and Project Overview

1.1. Introduction

Sweetpotato (*Ipomoea batatas (L.) Lam.*) is a root crop belonging to the morning-glory (*Convolvulaceae*) family. Sweetpotato plants are grown from slips (transplants) which are produced from vegetative seed stock or cuttings taken from already planted slips. Sweetpotatoes are planted mainly for the roots but based on seasonal conditions and personal interest of the farmer, they can also be planted for forage production (Frankow-Lindberg and Lindberg, 2003). Sweetpotatoes in the United States (US) are generally planted in late spring starting from May and harvested in late summer or early fall starting from August and going through November prior to freezing temperatures. The duration between transplanting sweetpotato slips and harvesting the fully-grown roots ranges from 90 to 150 days, depending on the cultivar type, soil type and environmental conditions.

1.2. Origin and Domestication

The sweetpotato is a storage root believed to be domesticated initially in Venezuela or Costa Rica in South America (Bovell-Benjamin, 2007). According to Srisuwan et al. (2006) the origin of the sweetpotato was somewhere around Mexico and north Venezuela. It is unclear yet as to when the sweetpotato was domesticated, although scientists believe that the sweetpotato was domesticated approximately 5000 years ago (Roullier et al., 2013; Cumo, 2015). There is much debate to the origin of domestication being South or Central America (Stoddard et al., 2013). The sweetpotato was believed to be introduced to China just before the 17th century. It is reported that Christopher Columbus found the natives of the West Indies eating a hardy root, sweetpotato, and took it to Europe with him in the late 16th century (Zhang et al., 2004). Sweetpotato roots were therefore being grown in Spain by the year 1600 and in Virginia, US by the year 1650, although it wasn't until the end of the 18th century when the sweetpotato became widely established in the US (Smith et al., 2009).

1.3. Health Benefits

Sweetpotatoes are not only a source of many nutrients including pro vitamin A carotenoids, vitamin C, zinc, manganese and iron but are also rich in anti-oxidants and fiber (Burri, 2011). It is known that sweetpotatoes, especially the orange fleshed cultivars, are a great source of β-carotene which is a precursor of vitamin A. According to the United States Department of Agriculture (USDA), a cup of mashed sweetpotatoes provide nearly 30 milligrams of β-carotene which is about two times the amount that is needed for the daily vitamin A requirement of the body. Vitamin A deficiency can result in permanent blindness in a medical condition called Xerophthalmia to which children are extremely susceptible in developing countries (Simonne et al., 1993; Burri, 2011). By providing the adequate amount of β-carotene, sweetpotatoes significantly reduce the risk of children developing Xerophthalmia. In a study done by Hotz et al. (2012), β-carotene rich sweetpotato have been shown to improve the vitamin A status of infants and children in rural Mozambique.

1.4. Growth and Practices

Sweetpotato is generally grown in a rotation period of at least two years to alleviate insect and disease problems. Sweetpotatoes are typically grown on raised rows approximately 8 to 10 inches high giving enough space for the roots to grow completely, with a plant-to-plant spacing of around 12 to 15 inches along the row and a center-to-center distance between rows at around 38 to 48 inches (Humphries and Abrams, 1975; Smith and Wright, 1994). Typical growth structure of the sweetpotato roots is shown in Figure 1.1. Hammerle (1970) attempted to check for any preferred style and direction of vine growth for sweetpotatoes but it was concluded that the growth of vines was completely random with no clearly visible growth pattern. Sweetpotatoes are inconsistent in their shapes and sizes, although most of them fall within the US No. 1 grade specifications (Wright et al., 1986). The laterals emerging from the sweetpotato vines can be 120 inches long with leaves at regular intervals and each sweetpotato plant developing between 2 to 8 roots on average (Humphries and Abrams, 1975).

Figure 1.1: Typical growth structure of a sweetpotato hill labeled (left) and in field (right)

Seem et al. (2003) observed a critical weed-free period of 2 to 6 weeks after transplant for the Beauregard variety with the US No. 1 marketable yields higher at an early transplant date in weed free plots compared to a late planting date in fields with weeds in them. Growth parameters of Beauregard and Evangeline varieties were examined by Gajanayake et al. (2014) with respect to the soil moisture and it was observed that adequate soil moisture levels improved the growth and development of the storage roots compared to deficit in soil moisture (below 0.1 $in^3\ in^{-3}$ volumetric water content). Villavicencio et al. (2007) observed that the growth temperature affected the root periderm lignin content, implying that the sweetpotatoes grown at higher soil temperatures are likely to be more resistant to skinning injuries. Edmunds et al. (2015) studied the effects of a wide range of growing conditions such as soil moisture, temperature, fertility and other growing practices on postharvest diseases to the roots by

Rhizopus soft rot and bacterial root rot in North Carolina and Louisiana and observed that there was a wide variation in disease incidences based on the field of study, although the soil temperature, nutrients and soil moisture seemed to have an effect on the disease onset for the roots.

1.5. Sweetpotato Production, Harvesting and Post-Harvest Practices

Sweetpotato is a major tropical crop grown throughout the temperate and tropical regions of the world. China is the largest producer of sweetpotatoes in the world (~85%) with the US producing over 35 million cwt (hundredweight) in 2017 (~1%) (USDA-NASS, 2018). In the US, sweetpotatoes are grown for its roots which are a good source of vitamins, minerals and fibers (Arancibia et al., 2018). Over 150,000 acres of sweetpotatoes were harvested in 2018 in the US (USDA-NASS, 2018) with North Carolina producing approximately 60% of the country's crop, a production value over $340,000,000 (USDA-NASS, 2017). Sweetpotatoes in North Carolina are generally grown in sandy coastal plain soils. Covington variety developed by Yencho et al. (2008) accounts for over 90% of North Carolina acreage (Smith, 2018). Bellevue and Beauregard (Rolston et al., 1987; La Bonte et al., 2015) varieties are also grown in some parts of North Carolina.

Bellevue variety in California has had a US No. 1 marketable yield greater than Covington and Beauregard for the majority of the field trials (La Bonte et al., 2015). Jewel variety was released by North Carolina in 1970 and is still grown by some of the farmers due to its excellent taste and baking qualities, although it is susceptible to soil rot (Smith et al., 2009). US No. 1 grade of the sweetpotato roots describes the shape and size of the sweetpotatoes as 3 to 9 inches length, diameter range between 1 -3/4 and 3 -1/4 inches and a maximum weight of 1 -1/8 lb (18 ounces) (Barkley et al., 2017; Thompson et al., 2017). In North Carolina most of the sweetpotatoes are not irrigated, but those that are irrigated use the center pivot system. In the US, more than 80% of sweetpotato storage roots harvested are used for human consumption and around 10% for cattle feed (Lebot, 2009). The ideal temperatures for sweetpotato growth are 75°F to 85°F during the day to enhance vegetative development and approximately 60°F to 70°F during the night to assist the formation of sweetpotato storage roots (Roullier et al., 2013).

Harvesting of sweetpotatoes intended for fresh market is generally done by hand where the roots are exposed on the ground surface by disc plows or chain diggers and a harvest crew goes about manually separating each root from the main stem and depositing them into bins. Sweetpotatoes which are intended for processed or canned products are harvested with any of the available commercial diggers based on the financial capability of the farmer as the quality of harvest is not important. Insufficient and unskilled labor along with an ever-changing federal policy involving labor add to the driving force for development of mechanized means, especially for harvesting sweetpotatoes in large amounts for fresh market purposes (Abrams et al., 1978). During harvesting and post-harvest handling of sweetpotatoes, the outer layer of periderm has a high chance of being separated from the underlying root tissue (Villavicencio et al., 2007). Sweetpotato roots which are ready to be harvested have delicate, easily damageable skin and are torn apart with the slightest of tangential force applied (Goodman and Hamann, 1971). Not only is skin damage cosmetically unacceptable, but also each injury site is a potential site of postharvest rots.

A standard practice for growers to reduce damage and abrasions to the roots at the time of harvest is to de-vine, which involves partial or complete removal of vines prior to harvesting. Generally, prior to harvest, the vines are mowed, which removes the leaves, but the extensive tangle of random above ground vegetation at ground level may remain intact causing difficulty for any harvesting equipment. According to experiments conducted by Dukuh (2011), defoliation of the sweetpotatoes prior to harvest significantly reduced the damage and rot during harvesting and post-harvest handling. Mechanical pre-harvest treatments such as de-vining as much as 14 days prior to harvest were deemed to be beneficial to reduce sweetpotato skinning compared to no treatments (Schultheis et al., 2000). Arancibia et al. (2013) observed that application of pre-harvest treatments such as ethephon to set the skin to reduce skinning damage during harvest (La Bonte and Wright, 1993) is likely to increase tip rot incidence for the Beauregard variety. Schultheis et al. (2000) reported that mowing up to seven days before harvest sets the sweetpotato root skin which may be beneficial to reduce damage during harvesting. Hayes et al. (2014) proposed a new method of undercutting the roots to eliminate water and nutrient supply for the roots to better initiate the skin setting process and enhance the skin strength of the sweetpotatoes prior to harvesting for reduced damage during harvest.

Curing of sweetpotatoes involves the roots being placed in a warm room or facility at a temperature of approximately 85°F with sufficient ventilation and a relative humidity of approximately 90% for 4 to 7 days immediately after harvesting depending on the temperature of the roots at the time of harvest (relative to the 85°F) (Abrams, 1984; Eiland et al., 1989; Edmunds et al., 2008). Curing is also known to be useful to set the sweetpotato skin preventing damage during postharvest handling (Blankenship and Boyette, 2002). Curing reduces postharvest losses as the curing process will cover the dead cells in the areas of the wounds (Lewthwaite and Triggs, 2012). Curing heals the cuts and damage to the roots, improving their visual appeal to the consumer. Ideal storage conditions for sweetpotatoes would be a well-ventilated storage area with temperature around 55°F and a relative humidity of around 90% (Boyette, 2009).

1.6. Project Overview

Complete mechanization of the sweetpotato harvesting operation has been difficult to achieve due to the vine growth structure and delicate skin of the roots at the time of harvest. It has already been established and supported by researchers that partial or complete vine removal as a pre-harvest operation would reduce the mechanical handling required to separate the roots during harvest and if achieved, would be a huge step towards successful mechanization of sweetpotato harvesting and field grading. 'Singulating' or isolating the roots from the stem and from each other prior to harvest is essential if the harvesting process is to be improved and this can be achieved by pulling the vines using soil as an anchoring medium as the sweetpotato roots remain underground, and then mowing them to avoid vine interference with the harvesting equipment. Several attempts have been made by researchers including Humphries and Abrams (1975) and Smith and Wright (1994) at developing a pre-harvest machine directed at achieving partial or complete vine-root separation.

North Carolina has witnessed over a 200% increase in production in the last 15 years with close to 90,000 acres being harvested in the 2018 season (USDA-NASS, 2018). The overall sweetpotato consumption in the country increased by around 90% in this time frame with the per-capita consumption being close to 8 pounds in 2017 (Statista, 2017). The sweetpotato processing industry has also expanded substantially in the last few years. All these factors in addition to ever-increasing farm wages result in the need of a pre-harvest machine aid to enable the mechanical harvesting of sweetpotatoes.

The understanding of the physical, structural and growth properties of the sweetpotato vines and roots along with the principles established in literature enabled us to design, develop and fabricate a two-row pre-harvest vine puller-chopper harvesting aid. This machine is capable of achieving nearly complete vine-root separation to aid the harvesting process in terms of improving harvesting efficiency, enhancing the root skin adhesion and reducing root damage during harvest. Field evaluation of the harvesting aid developed involved thorough testing in a wide range of soil, field and crop conditions to optimize the machine performance, overcome any clogging and breakdown issues, and establish power requirements to have a robust machine that can aid the harvesting process and enable mechanical harvesting of sweetpotatoes.

Performance evaluation of the harvesting aid involved testing for vine-root separation efficiency (Humphries and Abrams, 1975; Smith and Wright, 1994) of different sweetpotato varieties. Separation efficiency for a harvesting aid which aims to achieve complete vine-root (or main stem – root) separation can be defined as the percentage of main stems separated from the roots over the distance traveled by the machine. This can be both within a hill (the number of roots separated from the main stem divided by the number of roots in a hill) or overall (the number of hills with their main stems completely separated from the roots divided by the total number of hills encountered during the travel). The former yields the local separation efficiency, which can be measured when there are means to dig the roots and can be averaged over row lengths to compute the separation efficiency. The latter yields the overall separation efficiency, which can be easily measured when there are no means to dig the roots. The effect of vine-root separation by the harvesting aid in the resulting enhanced skin strength of the roots during harvest was studied. Different harvesting scenarios involving the developed harvesting aid were also studied to conduct a comparative economic study of using the vine puller-chopper harvesting aid in the current sweetpotato production process.

The objectives of the study were to:

(i) design and develop a robust mechanical harvesting aid capable of achieving complete vine-root separation and evaluate its performance in terms of separation efficiency in a wide range of field and crop conditions,

(ii) quantify the enhanced root skin adhesion due to vine-root separation by the harvesting aid over a 16-day period prior to harvest, and

(iii) conduct an economic study of different harvesting scenarios using the vine puller-chopper harvesting aid in the sweetpotato production process.

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CHAPTER 2: Design, Development and Field Evaluation of the Vine Puller-Chopper Harvesting Aid for Separation Efficiency

2.1. Abstract

With the increase in demand for quality sweetpotatoes and the ever-increasing farm labor costs, the sweetpotato industry is investigating the use of mechanical harvesting as a possibility in the near future. It is beneficial to remove the vine material produced by the sweetpotato plants prior to harvesting to improve the harvesting efficiency, control root growth and decrease the damage to the roots during harvest. Researchers have made several attempts over the last 60 years to build a machine that achieves complete vine-root separation, but success has been elusive. As a result, a robust harvesting aid machine to detach the main stem from the sweetpotato roots below the soil was designed and developed to achieve complete vine-root separation prior to harvesting. The harvesting aid developed consisted of a five-part system: pinch-rollers, mower, coulters, guide-vanes and the gauge wheel, to achieve the vine-root separation. The vine-root separation achieved by the harvesting aid would allow for field grading and sorting and better design the harvesting equipment for mechanical harvesting of sweetpotatoes for fresh market roots. Field testing of the vine puller-chopper harvesting aid involved a wide range of field conditions and varieties including Beauregard, Covington, Bellevue, Averre, and Jewel. Optimum rotational speeds (machine parameters) of the pinch-rollers and the mower were established as 180 rpm and 1200 rpm, respectively. The machine performance was evaluated in terms of separation efficiency for ground speeds up to 3 mph and the results obtained were consistent with those in literature with average separation efficiencies over 60% irrespective of crop variety, field or machine settings.

2.2. Introduction

Sweetpotatoes are typically grown on rows approximately 8 to 10 inches high giving space for the roots to grow and size completely in loose soil, with the spacing between hills being 12 to 15 inches along the row and a center-to-center distance between the rows being approximately 40 inches (Humphries and Abrams, 1975; Smith and Wright, 1994). Felix et al. (2015) evaluated Covington, Beauregard, Diane and Evangeline varieties for yield, vines per hill and vine length. They observed that Covington variety had about 6 vines per hill while Beauregard and Evangeline averaged 10 vines per hill with the vine length averaging at 40 inches, 80 inches and 60 inches for Covington, Beauregard and Evangeline respectively, and the vine length in general increasing with a decrease in soil water tension. Sweetpotatoes have variable shapes and sizes, although most of them meet US No. 1 grade specifications (Wright et al., 1986). Sweetpotato US No. 1 marketable yield decreased with an increase in soil water tension irrespective of variety (Felix et al., 2015). The laterals emerging from the sweetpotato vines can grow 120 inches along the row with leaves at regular intervals and each sweetpotato plant developing between 2 to 8 roots on average (Humphries and Abrams, 1975).

The above ground vine material is usually removed by operating a flail mower before harvesting (Smith and Wright, 1994). The mowing should be done carefully to not damage the sweetpotato roots just below the ground surface. Some growers do not put enough soil cover on top of the sweetpotatoes and have roots with their tops sticking out of the soil during harvesting. The configuration and unevenness of the row terrain makes it a difficult operation for mowing. Mowing the vine material is not enough to achieve complete vine-root separation for sweetpotatoes. Even after mowing the vines of sweetpotatoes, unlike the white potatoes, the storage roots remain attached to the main stem and lateral vines. Vines are removed from sweetpotatoes before harvesting with the purpose of destroying the strong underground linkage that exits between the main stem and roots so that the roots are isolated and need not be separated manually by a hand crew during harvesting (Hammerle, 1970). Hand separation of roots from the stem generally causes skinning and damage to the sweetpotato roots. The ‘snatching’ or pulling of sweetpotato vines prior to harvest to separate the foliage from the roots and ‘singulate’ or isolate the individual roots underground has been reported to aid in the harvesting process (Humphries and Abrams, 1975). Vine snatching involves two main actions. The first is to securely grasp the main stem or the vines and pull them with a force such that the main stem and vines are detached from the individual roots below the soil with the soil remaining intact or slightly disturbed. The soil medium can help serve as a restraining material against which the vines can be pulled. The second action removes the snatched vines and main stem by either throwing them or by cutting them into small pieces. These two mechanisms are essential for successful vine snatching.

2.2.1. Dynamics of vine-root separation

Hammerle (1970) examined the mechanical separation of sweetpotato roots from the main stem and estimated pulling velocities in the range of 5 to 10 mph with an associated energy requirement in the range of 7 ft-lb to 30 ft-lb. To achieve complete vine-root separation, the vines should be grasped and pulled as close to the soil as possible to prevent breakage of the vines during the pulling action. The direction of pull doesn’t seem to matter if enough force is applied to break off the main stem from the roots. However, it is known that an inclined direction of pull will require less force to achieve complete vine-root separation as compared to pulling them vertically. This is because in an inclined pull, the laterals growing in the direction of pull are not stressed and those on the other side of the hill are forced to resist a greater proportion of the applied pulling force. As these begin to break, the remaining laterals are stressed and break ultimately, resulting in a reduced maximum pulling force. In a vertical pull, however, all the laterals of the hill are subject to uniform load and offer resistance to being separated, thus requiring greater pulling force. According to Humphries and Abrams (1975) a slow rate of pull for the vines in sandy soil is more likely to pull the entire hill of sweetpotatoes above the soil surface instead of separating the vines from the roots below the soil. Humphries and Abrams (1975) found that a pulling velocity of less than 0.7 mph would most likely pull the hill up or not separate the main stem from the roots whereas a pulling velocity of more than 7 mph would snap the vine off at the point of pull and separate the vines from the roots. Humphries and Abrams (1975) studied the effect of vine pulling direction for different cultivars on the amount of force required to achieve the detachment of the roots from the main stem and reported average values of 30 lb and 50 lb for Centennial and Jewel varieties respectively with the values being reduced to around 25 lb and 45 lb respectively for an inclined pull at an angle of 60° from the vertical. Smith and Wright (1994) developed a two-row vine puller machine to separate the vines from the roots that had a pulling and chopping component and they reported the average combined power requirement for the two-row equipment as 11 hp.

O'Brien and Scheuerman (1969) conducted a study where they used a modified potato digger with a platform for sorting labor and bins to harvest sweetpotatoes after mowing the vines to a certain depth. They emphasized the dependence of quality of harvest on post-harvest handling processes and identified the need for vine removal prior to harvest which would lead to less labor required to detach the vines and cause less damage to the roots due to minimum harvesting and post-harvest manual handling. Harvesting of white potatoes and sweetpotatoes pose different problems which can be attributed to the difference in basic morphological and botanical characteristics of the crops. White potato which will have reached maturity easily detaches from the main plant while sweetpotatoes are difficult to detach from an actively growing main stem at the time of harvest and are firmly attached. Thus, higher energy inputs are required for sweetpotato than white potato to achieve complete vine-root separation mechanically (Humphries and Abrams, 1975). In the process of applying more energy using mechanical components, it only aggravates the tendency of the sweetpotato roots to skin more rapidly.

Kakahy et al. (2013) studied the cutting mechanics and cutting action of blades of the mower with respect to sweetpotato vine fragmentation, energy and efficiency of a possible harvesting machine component. Kakahy et al. (2013) analyzed three different blade angles at different mower speeds on resultant pulverization of sweetpotato vines in terms of their ability to pass through a sieve of given size and reported that a combination of 30° blade angle with a mower speed of around 2500 rpm achieved maximum pulverization and had minimum energy consumption. According to Kakahy et al. (2012) a blade angle of 30° to 40° with a rake angle of 10° to 20°, is better for chopping the vine material with a cutting speed of around 67 mph to achieve pulverization of the vine material. Kakahy et al. (2014) reported that the most effective cutting of the vines was achieved by the Y-shaped blade with a pulverization percentage of 82.76% compared to an L-shaped blade which achieved 76% pulverization. Kakahy et al. (2013) also reported that the vine pulverization percentage increased from 60% to 90% as the mower rpm increased from 1800 rpm to 2500 rpm irrespective of the shape of the cutting blade. Kakahy et al. (2013) reported that a flail mower was the most effective cutting equipment at speeds of 2300 rpm, where 60% of the cut vines could pass through a one-inch sieve. Furthermore, they reported that this percentage of cut vines increased if the moisture content of the vine was less, ideally around 30%. Hu et al. (2015) analyzed sweetpotato vine crushing shear forces during harvesting and observed that the shear forces to cut the vines were approximately 20 lb when the moisture content in the vines was 70% and that these forces increased to approximately 40 lb when the moisture in the vines was 45% and recommended a 6 to 8 day period between cutting the vines and harvesting. Ge et al. (2018) tested a hob-type roller for harvesting greens and observed that a cutting speed of 1200 rpm best optimized the machine performance when it cut the greens at a 25° angle.

2.2.2. Previous attempts at developing harvesting aids

Sweetpotato harvesting machinery development has mainly been for assisting the hand harvesting of fresh market produce with a select few for mechanical harvesting of roots for processing. Attempts made to adapt the carrot or beet root harvesters to achieve mechanical vine-root separation in sweetpotatoes prior to harvesting have failed (Hammerle, 1970). Any harvesting machine available commercially for fresh market sweetpotatoes are either semi-mechanized, with no significant reduction in labor or are rarely completely mechanized but can only be used for processed or canned produce due to the unacceptable levels of damage that they cause to the sweetpotato roots (Hammerle, 1970).

Hammerle (1970) constructed and tested a machine (Figure 2.1) to achieve mechanical separation of vines from the sweetpotato roots using the principle of horizontally rotating cylinders with a tapered inlet to assist the inflow of the vines, but only achieved 50% of stem-root separation for short rows of up to 50 ft. Hammerle (1970) proposed parameters needed for success designing harvest or pre-harvest machinery for sweetpotatoes and emphasized the need for vine destruction prior to harvest to reduce skinning and hand separation. The design considerations and sweetpotato growth parameters reported by Hammerle (1970) were later consolidated by Humphries and Abrams (1975).

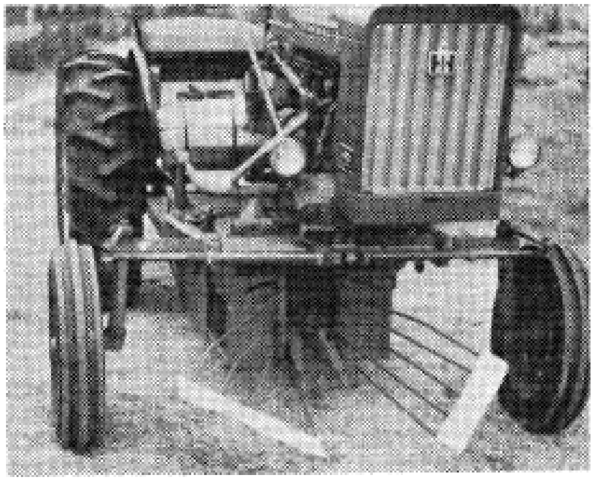

Figure 2.1: Experimental prototype of the de-vining machine developed by Hammerle (1970)

Burkhardt et al. (1971) tested a two-row self-propelled sweetpotato harvester (Figure 2.2) with an elevator chain mechanism using amplitude variation to achieve separation of vines and soil from the roots and proposed that vine removal prior to digging the sweetpotatoes need not be a separate operation but can be combined with digging into a single operation. The harvester designed in the study conducted by Burkhardt et al. (1971) was for row widths of 32, 34 and 36 inches and could travel at ground speeds up to 3 mph which is reasonable for sweetpotato machinery even today. The harvester developed by Burkhardt et al. (1971) also included coulters to cut the excessive lateral vines which were rooted and a hydraulically controlled gauge wheel to run according to the terrain of the field between rows. One drawback of the machine developed by Burkhardt et al. (1971) was the location of the gauge wheels. The gauge wheels operated in between the rows and not on top of the rows. The uneven terrain in between rows is generally different from the terrain on the ridge of the row where the sweetpotatoes are planted resulting in a lack of accuracy of machine components picking the sweetpotatoes up from beneath the ground leading to increased damage caused to roots by the harvesting equipment. A

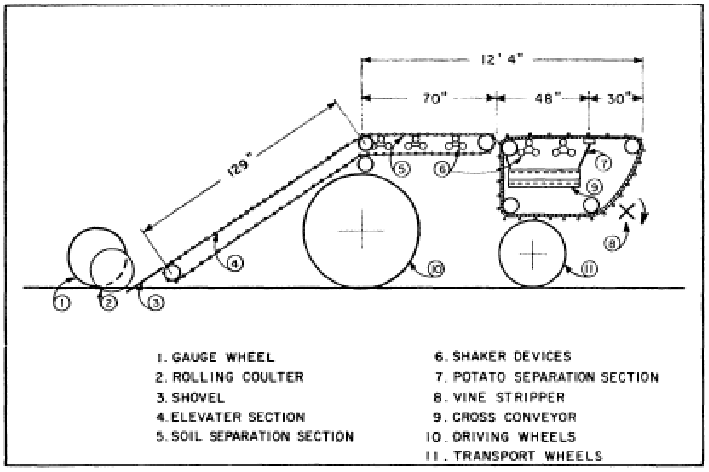

Figure 2.2: A schematic of the two-row self-propelled harvester developed by Burkhardt et al. (1971)

one-row harvesting aid was built and tested by Harris et al. (1973) based on the design by Burkhardt et al. (1971) and reported to increase the percentage of sweetpotato roots acceptable for fresh market. Completely automated harvesters cause excessive and unacceptable skinning damage to the sweetpotato roots because most of the sweetpotatoes are turned over by a plow and harvested manually by a harvesting crew (Srinivas, 2009).

Humphries and Abrams (1975) aimed at achieving vine-root and root-root separation by making use of the soil to act as a cushion prior to harvest to reduce the potential for damage in later manual separation. Humphries and Abrams (1975) reported that the average force required to achieve the vine-root separation was approximately 100 lb based on data collected using Centennial and Jewel type of cultivars. Humphries and Abrams (1975) evaluated three concepts (Figure 2.3) to achieve mechanical separation of sweetpotato roots from the main stem. One involved counter-revolving cylinders, the other inclined pneumatic tires, which were adopted from previous research. The third concept proposed by Humphries and Abrams (1975) was a new concept which utilized different sized roller drums with their axes oriented perpendicular to the direction of movement in order to grasp and pull the sweetpotato vines at their junction. The use of the roller drums was reported to have performed variably with main stem – root separation efficiency, measured by counting the number of hills with their main stems separated from the roots with respect to the total number of hills over the distance traveled by the prototype, in the range of 30% to 90% when tested on Jewel and Centennial cultivars. The major drawback of all the machines described in the study by Humphries and Abrams (1975) was an extra mowing operation was needed prior to the pre-harvest operation of vine-root separation which totaled three machine passes prior to harvest. This required a lot of horsepower and therefore was not economically feasible.

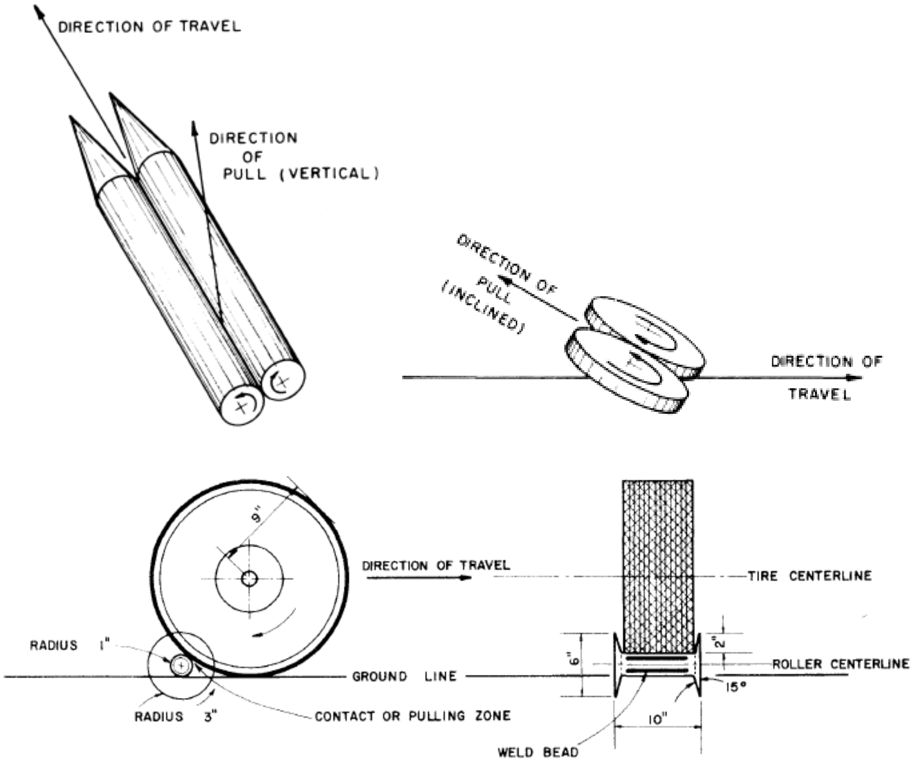

Figure 2.3: Schematic diagram of the counter-revolving cylinders (top, left), pneumatic tires (top, right) and the roller drums (bottom) concepts developed by Humphries and Abrams (1975)

The rise of mechanical aids for harvesting sweetpotatoes encouraged farmers to increase their farm acreage allocated for growing sweetpotatoes (Zahara and Scheuerman, 1969). Their research involved a harvesting aid which was tractor drawn and conveyed the dug roots past labor on trailers who were required to separate the roots from the main stem and guide the sweetpotatoes to the bins. This method was an alternative to the conventional method of hand harvesting. Zahara and Scheuerman (1969) reported a reduction in labor requirement of 40% for the harvesting operation due to the reduced time required for the deposition of sweetpotato roots into the bins with their proposed method. Harvesting aids, such as the one developed by Zahara and Scheuerman (1969), dug the roots and elevated them onto a horizontal working platform for laborers to perform the task of separating individual roots from the main stem by snapping them. This reduced the drudgery involved with hand harvesting and the labor requirements for the harvesting process (Abrams et al., 1978). Abrams et al. (1978) compared conventional hand harvesting methods with mechanical methods of harvesting into pallet bins and bulk transporters using Centennial and Jewel sweetpotato cultivars. They established that mechanical harvesting methods resulted in more damage and consequent weight loss of the sweetpotatoes. However, the extent of damage was such that the sweetpotato roots could be healed in the curing process.

Smith and Wright (1994) built a harvesting aid prototype (Figure 2.4) to achieve vine-root separation based on the model developed by Humphries and Abrams (1975) with custom design changes made to perform well in heavier soil and vine conditions in Louisiana. The prototype developed by Smith and Wright (1994) had two inclined condition rollers to grasp and pull the vines and added a mowing component to mow the snatched vines. This concept integrated the pulling and mowing operations and eliminated the need for an extra machine operation to mow the vines. Field tests conducted by Smith and Wright (1994) established a roller speed of 300 rpm for maximum vine-root separation efficiency, measured as the number of roots separated from the main stem in a hill divided by the total number of roots in the hill averaged over the distance traveled by the prototype, of 80% and reported that the performance of the prototype was heavily dependent on the tractor driver.

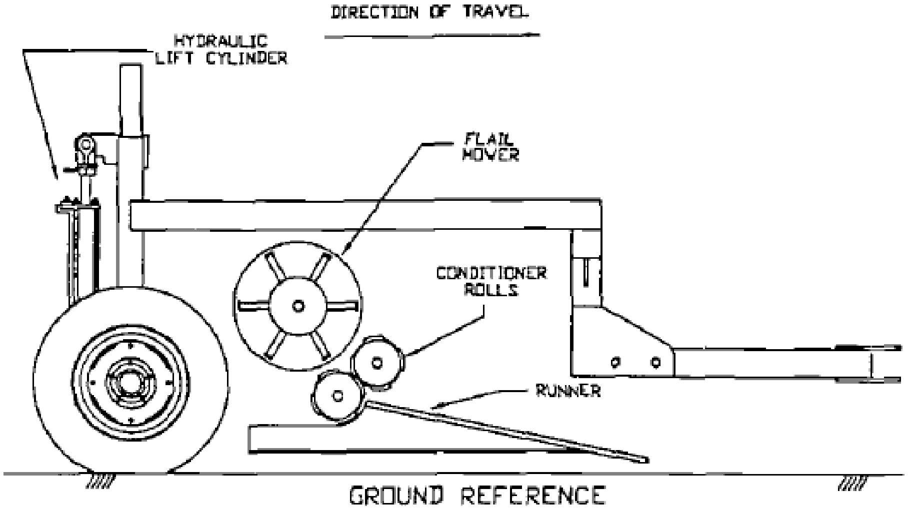

Figure 2.4: Side view schematic of the prototype developed by Smith and Wright (1994)

Flores (2018) analyzed a small-scale one-row conveyor-digger as a harvesting aid to reduce harvesting losses and labor cost. Flores observed that the intervention of the conveyor-digger in the conventional hand harvesting process can reduce damage during harvesting and increase the salable fresh market roots by at least 10% and reduce the labor costs by 50%.

The main challenge encountered by researchers has been to develop a machine consistent and robust enough to deal with the random growth pattern of sweetpotato vines and ensure that machine performance under field conditions was independent of external variables such as driver skill, soil type, cultivar type and density of vines. The major drawback of all the harvesting aid prototypes developed by researchers to achieve vine-root separation was that the continuous operation of the machine was sensitive to external factors and was limited to a few feet of rows (< 100 ft), which in present day scenario, would be inadequate to cover the acreage of sweetpotatoes being grown and economically not feasible to cover equipment costs.

2.2.3. Benefits of pre-harvest vine-root separation

It has been hypothesized that achieving vine removal prior to harvesting can have the added benefit of increasing the skin toughness and enhancing the sweetpotato root-skin adhesion (Schultheis, 2000; Hayes et al., 2014). Toughening the skin and increasing the adhesion will reduce damage during the handling necessary during harvesting and post-harvest processes. The first logical step, therefore, for developing a harvesting aid is to remove as much of the above ground material prior to harvest to avoid interference with any of the harvesting equipment (Humphries and Abrams, 1975; Smith and Wright, 1994) and possibly detach the main stem from the roots to initiate the skin setting process (Hayes et al., 2014) resulting in toughened root skin during harvest. The theory of de-vining the sweetpotatoes to increase skin toughness had been supported by multiple authors in the past including Smith and Wright (1994), however, none have extensively quantified the effect yet. Chapter 3 deals with the quantification of the skin strength enhancement of the roots over time due to the pre-harvest vine-root separation achieved by the vine puller-chopper harvesting aid described in this Chapter.

2.2.4. Importance of study

Complete mechanization of the sweetpotato harvesting operation has been difficult to achieve due to the vine growth structure and delicate skin of the roots at the time of harvest. It has already been established and supported by researchers that partial or complete vine removal as a pre-harvest operation would reduce the mechanical handling required to separate the roots during harvest and if achieved, would be a huge step towards successful mechanization of sweetpotato harvesting and field grading. North Carolina has witnessed over a 200% increase in production in the last 15 years with close to 90,000 acres being harvested in the 2018 season (USDA-NASS, 2018). The overall sweetpotato consumption in the country increased by around

90% in this time frame with the per-capita consumption being close to 8 pounds in 2017 (Statista, 2017). The sweetpotato processing industry has also expanded substantially in the last 15 years. All these factors, in addition to ever-increasing farm wages, suggest for the great need of a pre-harvest machine aid to enable the mechanical harvesting of sweetpotatoes.

2.2.5. Objectives

The understanding of the physical, structural and growth properties of the sweetpotato vines and roots, the principles of vine pulling, and chopping, established in literature and several attempts made by researchers at developing a successful harvesting aid to detach the main stem from the roots enabled us to design, develop and fabricate a two-row pre-harvest vine puller-chopper harvesting aid. The aim was to be capable of achieving complete vine-root separation to aid the harvesting process. Field evaluation of the harvesting aid developed involved thorough testing in a wide range of soil, field and crop conditions to optimize the machine performance, establish power requirements and have a robust machine to aid the harvesting process and enable mechanical harvesting of sweetpotatoes. The objective of the study was to design and develop a robust mechanical harvesting aid capable of achieving complete vine-root separation and evaluate its performance in terms of separation efficiency in a wide range of field and crop conditions.

2.3. Methodology

The most successful design to grasp and pull the vines close to the ground surface was achieved by the counter-revolving cylinders which was an evolution of the original design by Humphries and Abrams (1975) and later modified by Smith and Wright (1994). Years of research in various techniques of mechanically detaching sweetpotato main stems from their roots by several researchers manifested into the design by Smith and Wright (1994) as explained in section 2.2. Similar concepts were used in building a one-row prototype of the vine puller-chopper harvesting aid with quite a few deviations and advancements in the design.

2.3.1. Evolution of the vine puller-chopper harvesting aid

2.3.1.1. Design and development of the one-row prototype

The sweetpotato vines grow up to 15 inches or more from the ridge surface. There needs to be sufficient length of the grasping device to hold the vines and pull them. The pinch-rollers were used as the grasping and pulling mechanism in the one-row prototype design. The pinch-rollers (Figure 2.5) were built with steel tubing with a 6 OD X 3/8 wall (6-inch outer diameter and 3/8-inch wall thickness). Twelve flat bars made from half-inch key stocks were welded to the tubing at 30° intervals. The pinch-rollers were 18 inches long to hold no more than three sweetpotato hills at a time for grasping and pulling.

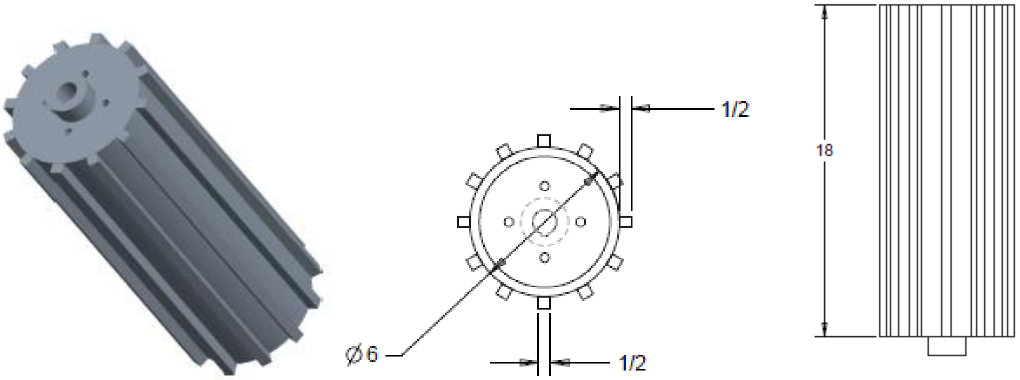

Figure 2.5: The pinch-roller drum (left), front view (center) and top view (right) schematic (all dimensions in inches)

Guiding the vine flow into the pre-harvest machine was always a challenge for researchers building sweetpotato vine removal equipment. To achieve vine flow into the harvesting aid system a set of tapered cones (Figure 2.6) were built using 12 GA (0.105 inch) HR sheet and welded as an extension to the pinch-rollers. The tapered roller-cones were 12 inches long and had diameters of 6 inches where it was welded to the pinch-roller drum and 2 -5/8 inches at the other end. One-quarter inch HR circular plates were used at the ends of the pinch-rollers and cones to complete the design with them being 5 -1/2 inches in diameter at the beginning and end of the rollers and 2 -1/2 inches for the end of the tapered cone. A quarter-inch round rod was welded around the tapered cone with a pitch of 2 -5/8 inches to form an auger type action for aiding the vine inflow into the system. The total length of each of the pinch-roller assembly with the tapered cones was 32 inches long. A 39-inch round rod of 1 -3/16-inch diameter was used with a 1/4-inch x 1/8-inch key-seat as a drive shaft to be able to rotate the pinch-roller assembly with a hydraulic motor. A schematic of the entire pinch-roller assembly with the cone extension and welded rod is shown in Figure 2.7. The idea was to use a set of these

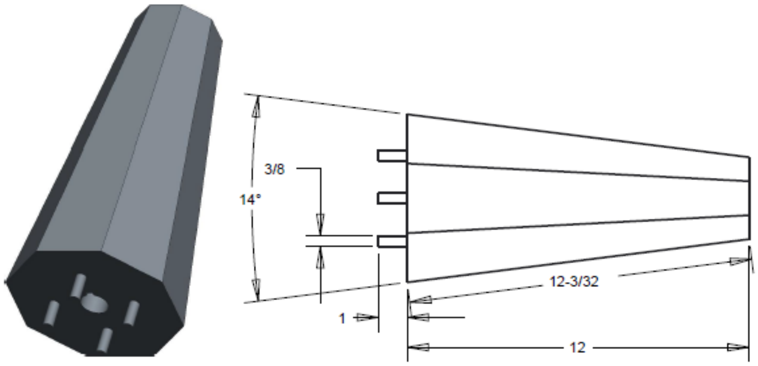

Figure 2.6: Tapered cone extension (left) and a schematic front view (right) (all dimensions in inches)

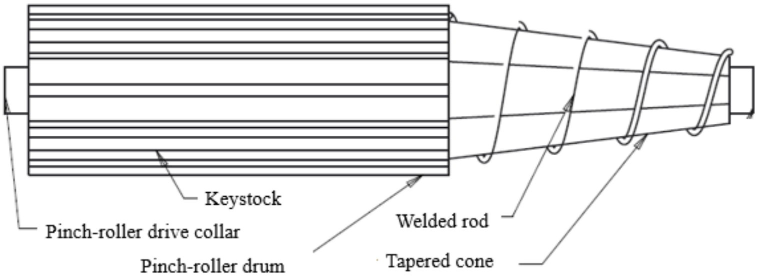

Figure 2.7: A schematic of the pinch-roller assembly with the tapered cone and welded rod

counter-rotating pinch-rollers (Figure 2.8) with the key stock to have several ‘pinch-points’ for the vines and main stems as the machine traveled along the row to grasp and pull them close to the ground surface.

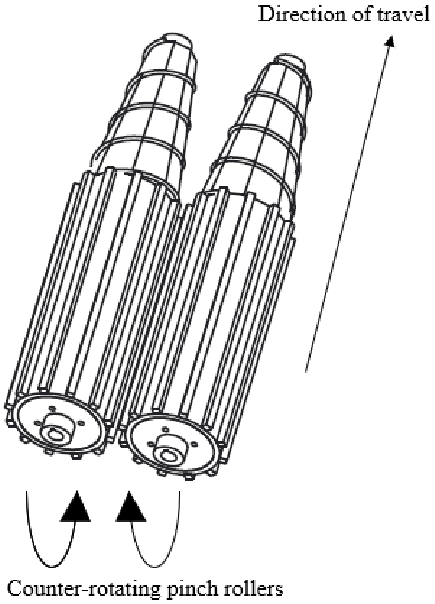

Figure 2.8: A schematic of the counter-rotating pinch-rollers to grasp and pull the vines

A set of guide-vanes were built using steel round rods to be placed at the end of the pinch-roller assembly and fastened to the sub-frame holding the pinch-roller assembly with nuts and bolts. The guide-vanes, consisting of a welded assembly of 8 round rods of diameters varying from 1/2 inch to 1/4 inch, were built to lift the vines from the soil surface and guide them into the pinch-roller assembly. The 8-inch long guide vanes (Figure 2.9) could lift the vines from the soil surface to a height of 7 -1/2 inches.

The pinch-roller assembly (with the pinch-rollers and tapered-cones) with the guide-vane components was mounted on a subframe made of four 2-inch x 2-inch square steel tubing with a wall thickness of 1/4 inch. The pinch-roller assembly was mounted using two 2-inch x 1-inch

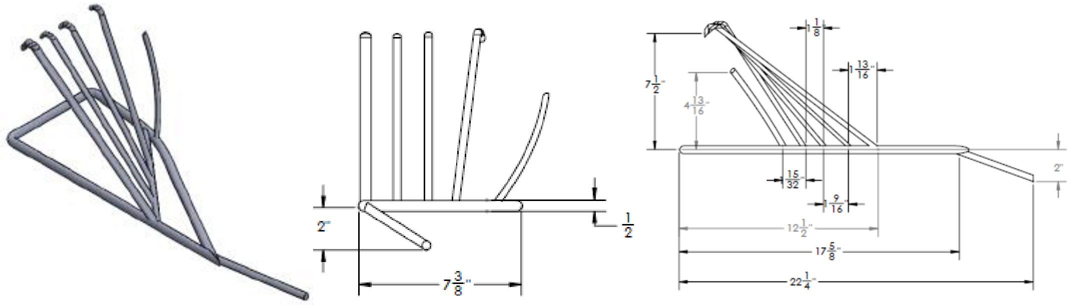

Figure 2.9: Guide-vane (left), front (center) and side view (right) schematic (all the dimensions in inches)

rectangular steel tubing of length 28 inches with a wall thickness of 1/8 inches. The pinch-roller assembly was mounted such that the gap between the pinch-rollers for the 18-inch ‘pinch-point’ section was less than 1/2 inch. The subframe holding the pinch roller assembly with the guide-vanes was mounted to the 72-inch-long main frame made of 2-inch x 4-inch x 1/2-inch rectangular tubing using four 12-inch-long swing plates.

A flail mower (Figure 2.10) component with flat blades was mounted on top of the pinch-roller assembly aligned perpendicular to the direction of travel to chop the vines being pulled up by the counter-rotating pinch-rollers and maintain the vine flow as the harvesting aid traveled along the row. The mower component was 25 inches wide and consisted of an assembly of two

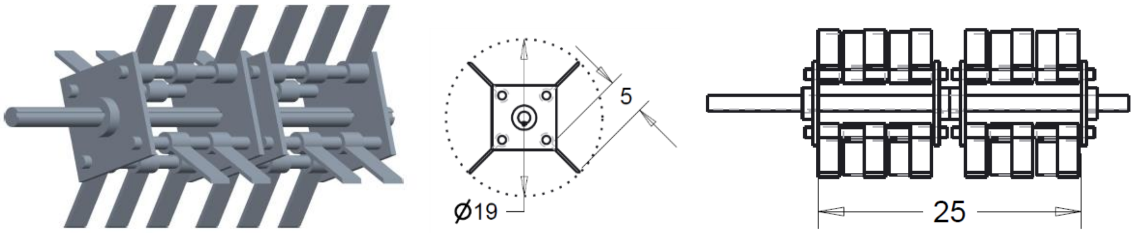

Figure 2.10: Flail mower with flat blades (left) with side view (center) and front view (right) schematic (all dimensions in inches)

mower heads, each constructed by a set of 8-inch x 8-inch x 1/2-inch square steel plates, 11 inches apart, connected by four 1-inch round rods at each corner with blades attached to them. A total of 20 flat blades of length 5 inches were used for the mower. A 40-inch round rod of 1 -1/2-

inch diameter was used with a 1/2-inch x 1/4-inch key-seat as a drive shaft to be able to the mower with a hydraulic motor. Due to design constraints the flail mower could not be very close to the pinch-rollers and there was a considerable gap of around 6 inches between the top surface of the pinch-rollers and the reach of the flail mower blades.

A 20-inch cylindrical drum (Figure 2.11) was used as a gauge wheel for the one-row prototype and it was mounted at the end of the subframe holding the pinch-roller assembly using a four-bar linkage mechanism. The gauge wheel was essential to the design because it removed much of the complexity encountered by many researchers of having a harvest assist machine follow the exact terrain of the rows in the sweetpotato field. For grasping and pulling the vines along a row, it is essential that the machine components dealing with the vines be always parallel and as close to the ground surface as possible. With uneven row heights and contours in most of the sweetpotato fields, many researchers had difficulty making a machine that can accommodate terrain variations which significantly affected the performance of the developed prototypes. Researchers developed guide wheels that were placed in between the rows to support the machine and this terrain was in many cases different than the row terrain itself. The four-bar linkage of the gauge wheel enabled the machine to float entirely on the gauge wheel which

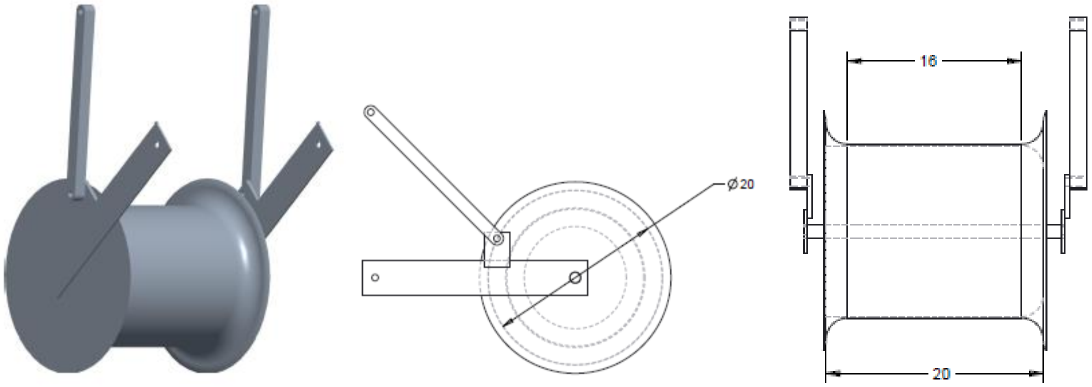

Figure 2.11: Gauge wheel with four-bar linkage (left), side view (center) and front view (right) schematic (all dimensions in inches)

followed the row terrain, no matter how uneven the row was, and was independent of the terrain in between the rows in the field. This was very influential in creating a robust design capable of operating in a wide range of soil, field and crop conditions and not being very sensitive to field changes. Another purpose of the gauge wheel was to compress the soil disturbed by the guide-vanes and the pinch-rollers and make it compact for digging.

A set of sharp-edged fluted coulters of 24-inch diameter were assembled to the main frame of the design to run in front of the pinch-roller assembly. The coulters would detach the vines and laterals that were re-rooted to either side of each row and reduce the amount of vine flow into the system. The one-row prototype design assembly made in Creo Parametric 3.0 is shown in Figure 2.12 and a drawing with basic dimensions is shown in Figure 2.13. The entire prototype would be connected to the rear of a tractor using the three-point hitch and the main frame of the harvesting aid was designed accordingly. A schematic of the one-row prototype is shown in Figure 2.14 and the one-row prototype during field testing is shown in Figure 2.15.

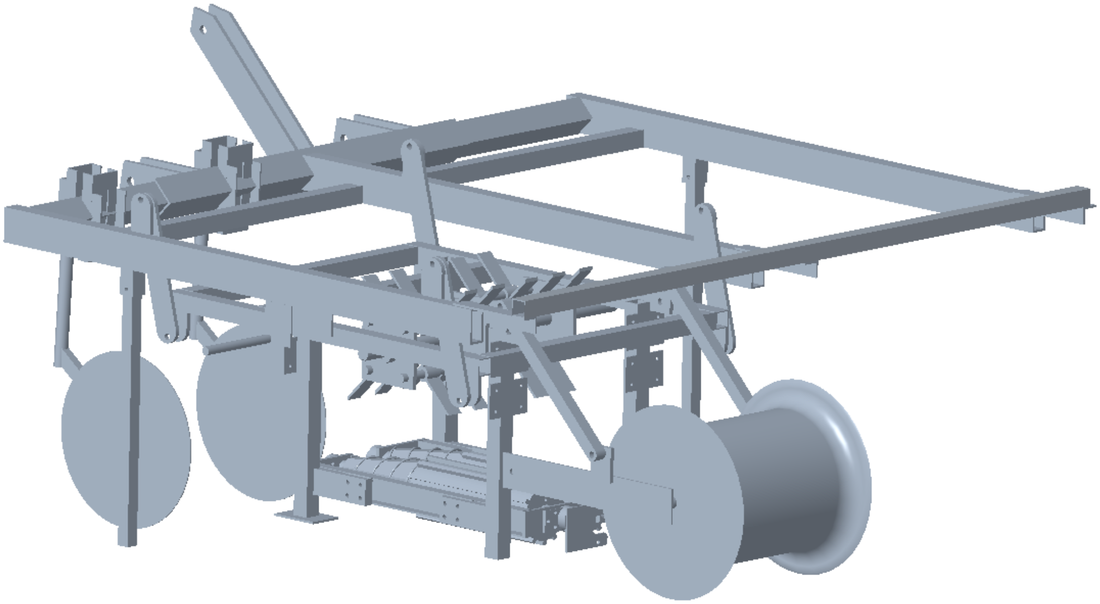

Figure 2.12: One-row prototype of the vine puller-chopper harvesting aid

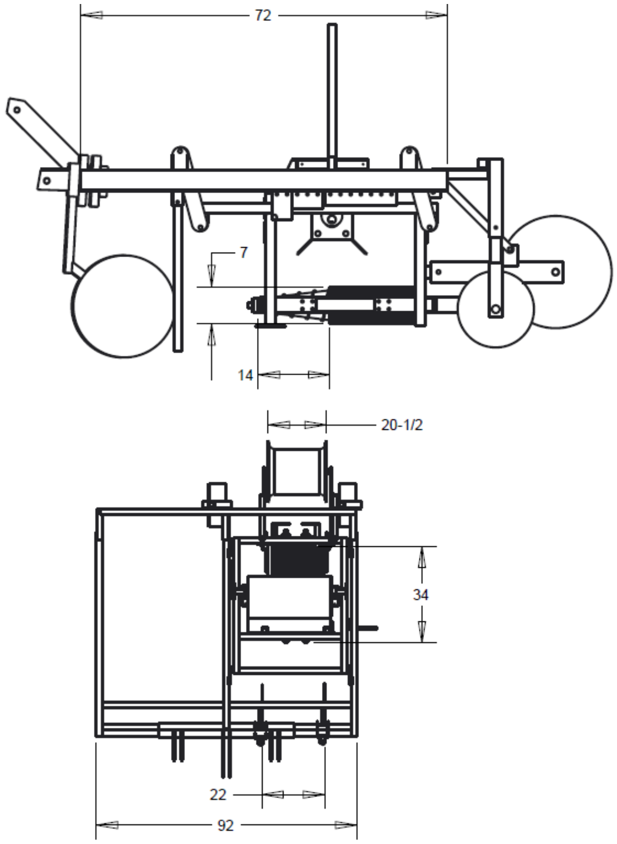

Figure 2.13: Drawing with basic dimensions (in inches) of the one-row prototype harvesting aid

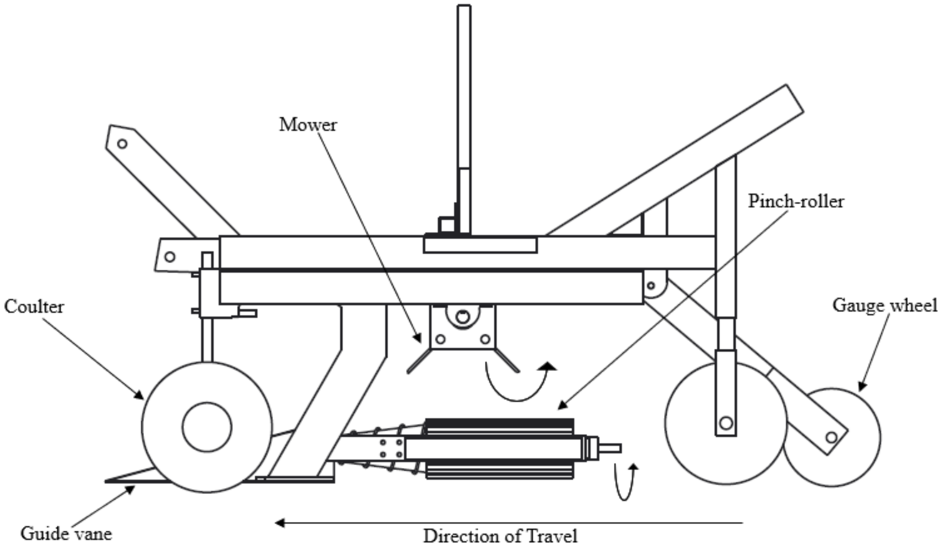

Figure 2.14: A schematic of the one-row prototype of the vine puller-chopper harvesting aid

Figure 2.15: One-row vine puller-chopper prototype field testing during the 2014 harvesting season

The pinch-rollers and the flail mower were designed to operate with the use of hydraulic motors. To select the appropriate hydraulic components for the pinch-rollers and the mower, the torque, flow rates and power were calculated. The force required to pull the vines vertically to achieve vine-root separation was measured using a mechanical force gauge (D-200, AMETEK, Largo, FL) with a maximum range of 200 lb, over several fields and crop varieties. The peak value was approximately 120 lb. This value is within the range of force measurements required to pull the sweetpotato vines found in literature (Hammerle, 1970; Humphries and Abrams, 1975; Smith and Wright, 1994). Therefore, a peak value of 120 lb was selected as a reasonable assumption of the force required to pull a hill of vines. The pinch-roller length designed for the vine puller-chopper harvesting aid was 18 inches. This would at a time hold no more than three hills of sweetpotato simultaneously based on the conventional plant spacing (Schultheis et al., 1999; Smith et al., 2009; Meyers et al., 2010) practiced by growers. If the harvesting aid pulled all three hills at once, the maximum force required would be 3*120 ~ 360 lb. The pinch-roller diameter was 6 inches and the corresponding torque was determined for the pinch roller trying to pull these vines as 360*3 = 1080 lb-in. When shared by 2 motors, the torque is reduced in half and is approximately 525 lb-in. A conservative approach was used for the maximum torque case as it was assumed that only one motor does all the work lifting the vines. Most tractors had a maximum flow rate of 26 gallons per minute (gpm). Using the torque and the known flow rate, the hydraulic motors were sized. In the case of the mower, it was established that the vine crushing shear forces during harvest to cut or chop the vine material to achieve pulverization were less than 50 lb (Kakahy et al., 2013; Hu et al., 2015). The cutting diameter of the mower was 19 inches and the corresponding torque was determined for the mower as 50*9.5 = 475 lb-in. A high speed, low torque motor was needed for the mower whereas a low speed motor with a relatively higher torque was needed for the pinch rollers. The hydraulic system for the one-row vine puller-chopper harvesting aid is depicted in Figure 2.16.

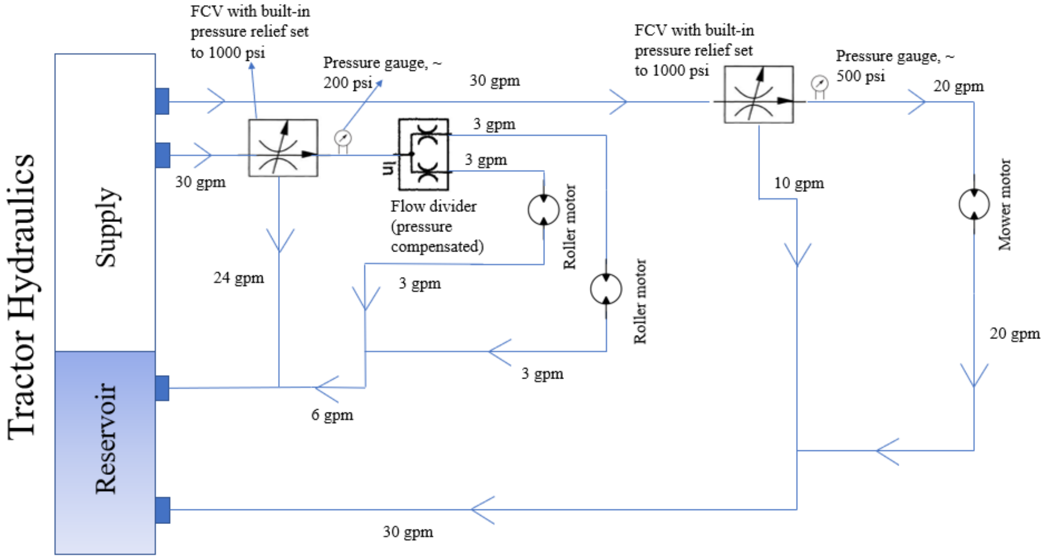

Figure 2.16: A schematic of the hydraulic circuit for the one-row vine puller-chopper harvesting aid

Generally, remote hydraulic outputs on a tractor is 30 gpm or less. Thus, a 0 to 30-gpm flow control valve (FCV) is sufficient. The thirty-gallon range was the largest available and was selected. Some tractors had flow control valves to adjust the flow rate, while most of them were on/off with fixed or zero flow rate, without any control over smaller increments of the flow rate.

The relief pressure was set at 1000 psi using the needle spring system adjustment. The pressure relief valve is a safety device and the relief pressure needs to be set to limit the hydraulic system pressure in case the system is over-loaded. The pressure relief allows the system to bypass the hydraulic fluid back to the reservoir (tank) in case the relief pressure setting is reached. The spring tension is adjusted by turning the nut and the relief pressure is directly proportional to the spring force. Often the mower or the pinch-rollers were reversed to unclog the vines. For the mower, the relief setting restricts the pressure buildup and allows the fluid to be in the circuit. This makes the high speed, low torque motor spool down when it is cut off. This may also be done with the tractor internal hydraulic control valves if available. When the rollers clog and stop rotating, the pressure relief opens and bypasses the full flow back to the tank. However, practically, it lowers the pressure and keeps some fluid in the circuit. The pinch-roller motors were connected in parallel for the one-row prototype to maintain the same flow rate and operate independently.

2.3.1.2. Fluid power calculations

Field testing of the one-row prototype involved determining the operating pressures, flowrates, power and torque requirements for the harvesting aid. The operating pressures of the mower and the pinch-rollers were measured during the operation of the harvesting aid with a hydraulic pressure gauge (VI-53821, Northern Tool & Equipment, Burnsville, MN). The rollers were operating at approximately 200 psi and the mower was operating at approximately 500 psi. Consequently, the motor flow rates required for the mower and the pinch-rollers were calculated based on the measured speeds and displacement of the motor. The mower rpm and the pinch roller rpm were also measured during field testing in the 2014 and 2015 harvesting seasons with a tachometer (CDT-1000HD, Electromatic Equipment Inc., Cedarhurst, NY) and were estimated at a maximum of 1600 rpm for the mower and 300 rpm for the pinch-rollers with normal operation at approximately 1200 rpm for the mower and 180 rpm for the pinch-rollers.

For a 3.75 in^3 motor displacement hydraulic motor (DH 50-3825, Sauer-Danfoss Company, Ames, IA), and a motor speed of 1200 rpm, the operating gallon per minute (gpm) flowrate, assuming 100% efficiency, can be calculated as: gpm (mower) = motor displacement*rpm/231 = 3.75*1200/231 ~ 20 gpm. For a 3.75 in^3 motor displacement hydraulic motor (DH 250-2604, Sauer-Danfoss Company, Ames, IA), and a motor speed of 180 rpm, the operating gallon per minute (gpm) flowrate, assuming 100% efficiency, can be calculated as: gpm (pinch-roller) = motor displacement*rpm/231 = 3.75*180/231 ~ 3 gpm. The theoretical fluid power and torque for the mower can be calculated as follows: **Mower:** rpm ~ 1200, pressure ~ 500 psi, flow rate ~ 20 gpm; **Fluid Power** = pressure*flow rate = 500*20 psi-gpm = 500*20/1714 hp = 5.83 hp; **Torque** = 63,025*power/rpm = 63,025*5.83/1200 ~ 306 lb-in. The theoretical fluid power and torque for the pinch-roller can be calculated as follows: **Pinch-roller:** rpm ~ 180, pressure ~ 200 psi, flow rate ~ 3 gpm; **Fluid Power** = pressure*flow rate = 200*3 psi-gpm = 200*3/1714 = 0.35 hp; **Torque** = 63,025*power/rpm = 63,025*0.35/180 ~ 123 lb-in.

2.3.1.3. Development of an improved one-row prototype

Field testing in terms of performance evaluation for the one-row prototype involved operating the harvesting aid in a wide range of soil, field, crop and environmental conditions to improve the design of the prototype. Most of the testing was done at Burch Farms, Faison, NC and Tull Hill Farms, Kinston NC. It was observed that the guide-vanes, pinch-rollers, coulters and the gauge wheel all served their design purpose in terms of functionality. However, the flail mower did not seem to achieve its potential in terms of chopping the vine material to maintain the vine flow. The flail mower was too high above the pinch-rollers due to design constraints and chopped fewer vines that were being grasped and pulled by the counter-rotating pinch-rollers. In addition, the mower was aligned perpendicular to the direction of travel along the row and hence did not do an effective job to dispose the chopped vines away from the harvesting aid. The chopped vines fell back on top of the pinch-rollers and caused clogging of the rollers after a running few rows. Also, the mower covered a chopping length of only up to 4 inches of the 18-inch-long ‘pinch’ zone of the pinch-rollers. The remaining 14 inches of the pinch-rollers were pulling the vines up into the system, but the mower was unable to chop them due to design issues which hindered maintaining the vine flow and would cause stoppages. The mower was thus a limiting factor that negatively affected the performance of the harvesting aid which was unable to handle dense vines and a variety of crop conditions. This led to redesigning the one-row prototype to accommodate an axial mower oriented with the direction of travel (parallel to the row) and disposing the vine material chopped along the complete 18 inch ‘pinch’ zone of the pinch-rollers to the side of the rows (perpendicular to the row). The 36-inch mower (Figure 2.17) was made of 4 -1/2-inch OD tubing with a wall thickness of 3/16 inch and used Y-shaped blades to achieve improved vine chopping as suggested by Kakahy et al. (2013).

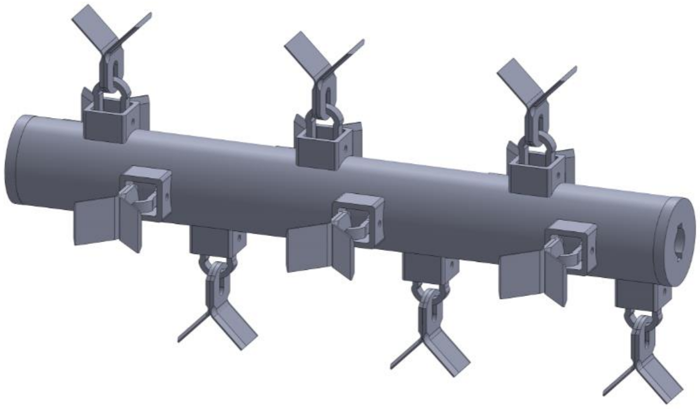

Figure 2.17: Axial mower with Y-shaped blades for improved performance of the one-row prototype

A 1 -3/16-inch drive shaft was used to drive the mower using a hydraulic motor, like the original prototype. The mower length extended beyond the tapered-cones of the pinch-roller system and started pruning the vine material even before it entered the pinch-roller system. This provided more control in dealing with the vine height in any field. The mower blades (Caroni Flail Rotor Blades – Type B, Agri Supply of Garner, NC) were approximately 3 -5/8 inches long. Two blades were fastened with a spacer in between them using nuts and bolts inside a rectangular casing made of small segments from 2-inch x 4-inch x 1/4-inch tubing, each segment cut at the end with the same curvature of the mower tubing and welded to it. The fastening of the two blades into a blade set made the blade set into a Y-shape that previously had maximum chopping efficiency (Kakahy et a., 2013). A total of 24 blades were used and their placement was staggered on the mower tubing at right angles with a spacing of less than 5 inches between each blade set. The redesigned one-row prototype with the axial mower is shown in Figure 2.18.

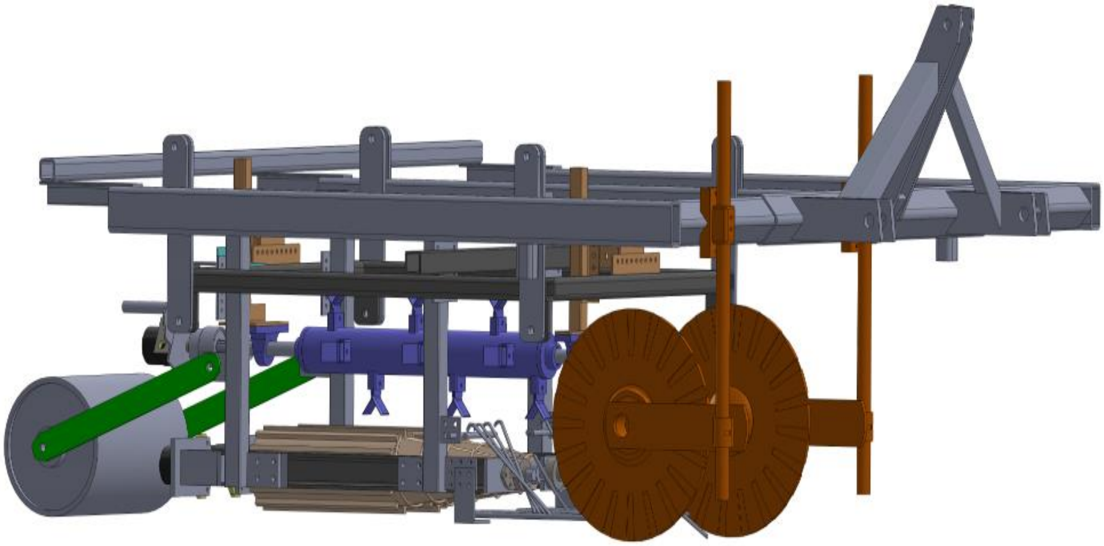

Figure 2.18: Improved one-row prototype designed with axial mower, and adjustments for mower height and guide-vanes

The continuous action of pulling the vines into the system and chopping them off with the new mower design helped to maintain the material flow much better than the original design.

The design was improved by positioning the mower (Figure 2.19) to within an inch above the pinch-rollers to chop the vine material being pulled. The mower height was made adjustable to accommodate different crop conditions. The guide-vanes also were made adjustable according to the field conditions in this improved design. This enhanced the flexibility, functionality and performance of the one-row prototype substantially and the harvesting aid was able to function in most of the crop, field and environmental conditions that it was tested.

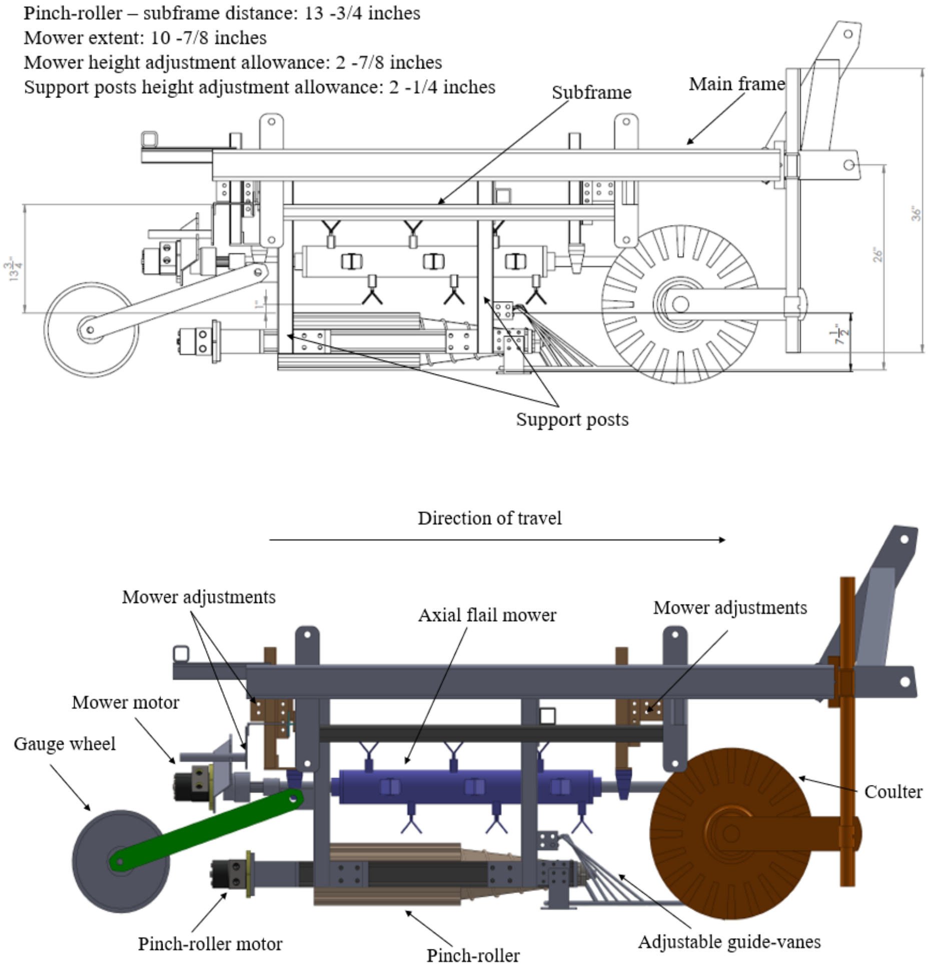

Figure 2.19: Improved one-row prototype (drawing above; design below) harvesting aid with an axial mower and Y-shaped blades along with mower and guide-vane adjustments (all dimensions in inches)

Much of the field testing (Figure 2.20) during the 2015 harvesting season with the improved one-row prototype of the harvesting aid was successful. The harvesting aid could handle dense, thick vines in sandy, clay, dry or wet soils and achieve an average separation efficiency of approximately 60% irrespective of the crop variety and field conditions, which was by itself a huge improvement from the previous attempts in literature. A CASE MAXXUM 125 tractor was used for most of the testing. The vine puller-chopper harvesting aid needed adjustments for the coulter, gauge wheel height and the tractor height for a new field depending on the crop and soil type. Once the settings were adjusted to the field conditions, the harvesting aid performed consistently and continuously over a 1000 ft row distance amounting to an acreage of over 0.3 acres, without any clogging issues. Clogging plagued previous designs.

Figure 2.20: Field testing of the improved one-row vine puller-chopper harvesting aid hitched to a CASE 125 MAXXUM tractor in a field with the Covington sweetpotato variety, Burch Farms, NC

2.3.1.4. Two-row vine puller-chopper harvesting aid

During the 2016 harvesting season a collaboration was made with AMADAS Industries of Suffolk, VA, to build a two-row semi-commercial unit based on the improved one-row prototype design for further testing. One major change that was made in this design was the further extension of the mower (Figure 2.21) to 60 inches in length to prune the vines prior to entering the vine puller-chopper system through to the end of the pinch-rollers. This was done because it was observed during the testing of the previous designs that cutting the vines ahead of entering the vine puller-chopper system provided more control in handling dense vines and also minimized clogging at the end of the pinch-rollers due to accumulation of vines. This further enhanced the machine performance for the two-row unit. The mower consisted of a total of 84 Y-shaped blades. The 5 -3/8-inch length mower blades (Caroni Flail Rotor Blade – Type A, Agri Supply of Garner, NC) were used for the initial segment of the mower which protruded in front of the guide-vanes to cut the vines to a shorter desired length. For the remaining section of the mower, the shorter Type B blades were used as in the previous design, due to space constraints. The mower's orientation with respect to the other machine components is shown in Figure 2.22.

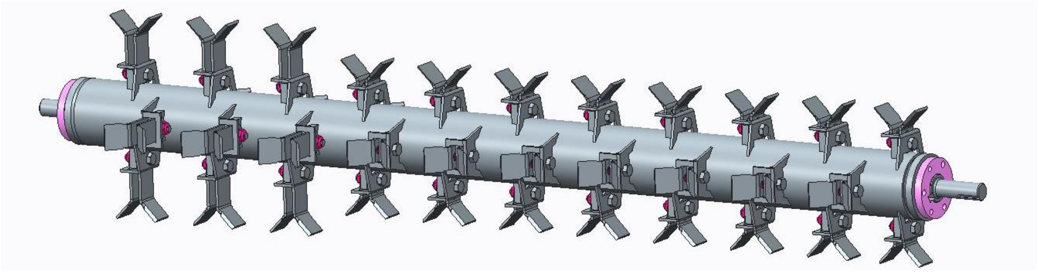

Figure 2.21: The 60-inch extended mower with a total of 84 Y-shaped blades

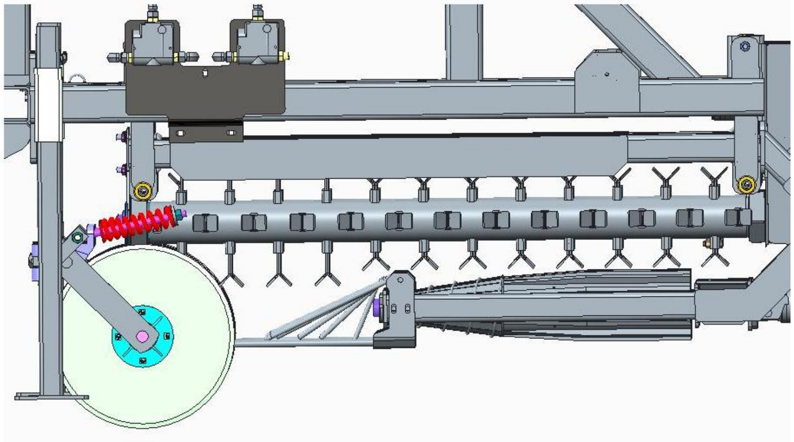

Figure 2.22: Orientation of the new mower with respect to the guide-vanes, pinch-rollers and the coulters

The two-row semi commercial unit of the vine puller-chopper harvesting aid is shown in Figure 2.23. The machine was designed to operate in fields with row spacing between 36 and 48

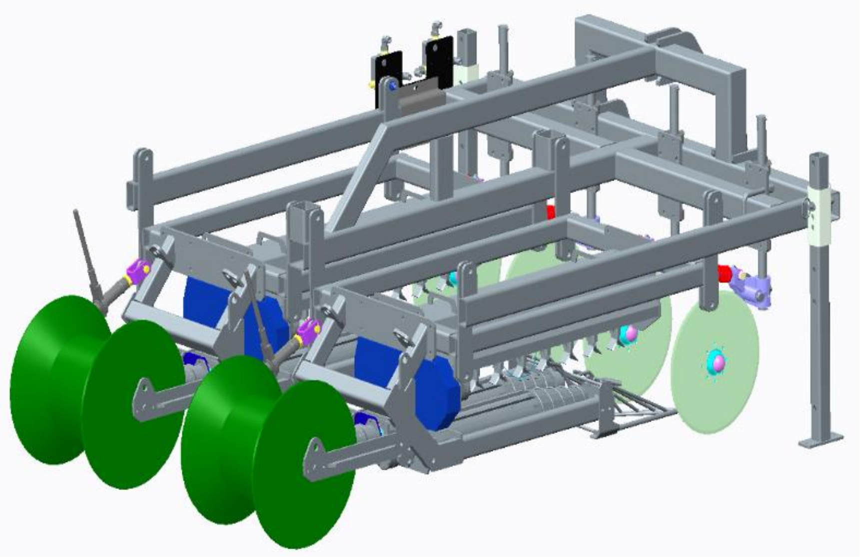

Figure 2.23: The two-row vine puller-chopper harvesting aid design adapted from the improved one-row prototype

inches. The fluid power, torque and power requirements were calculated for the two-row unit like they were for the one-row unit. Each row had a set of hydraulic driven pinch-rollers and mower, a set of coulters, a set of guide-vanes mounted in front of the pinch-rollers, and a gauge wheel at the end to carry out the vine-root separation achieved by the one-row prototype on two rows simultaneously. The total fluid power and torque required for the two-row harvesting aid were calculated as follows: **Both Pinch Rollers combined:** Fluid Power = 2*0.35 = 0.7 hp; Torque = 2*123 = 246 lb-in. **Total Fluid Power (per row):** Mower Power + Pinch-Rollers Power = 5.83 hp + 0.7 hp ~ 6.6 hp. **Total Torque (per row):** Mower Torque + Pinch Rollers Torque = 306 lb-in + 246 lb-in ~ 550 lb-in. This is the theoretical (minimum) power requirement since the mechanical and volumetric efficiency of the hydraulic motors are considered to be unity. The hydraulic system for the two-row vine puller-chopper harvesting aid is shown in Figure 2.24. The check valve in this design allows the fluid to loop in the circuit until the mower stops or spools down. The pinch-roller motors in each row are connected in series in this design.

The pinch-roller motor set of each row is connected in parallel with the adjacent row set. The mowers for each row are connected in series.

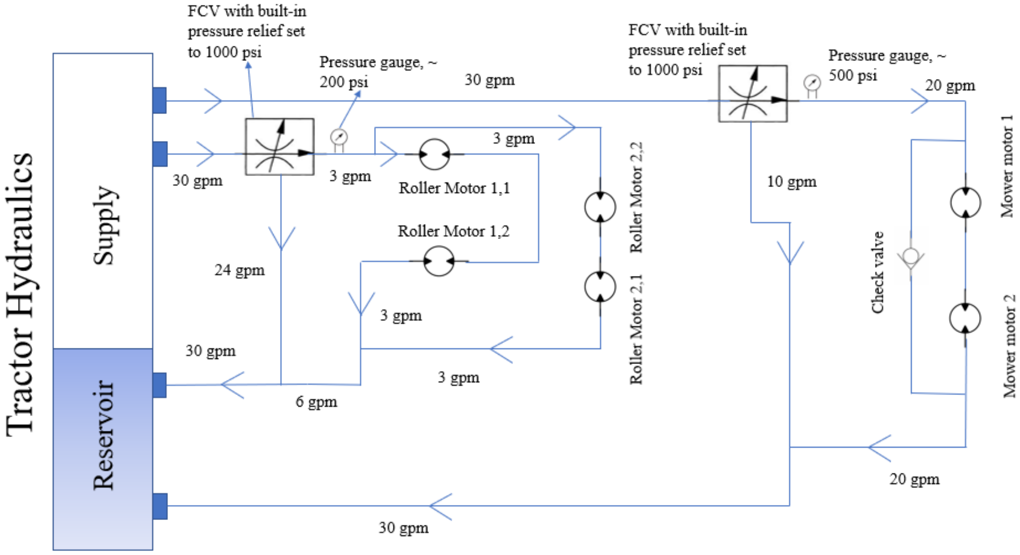

Figure 2.24: Hydraulic circuit schematic for the two-row vine puller-chopper harvesting aid

Considering the total hydraulic power required and the approximately 3,000 lb machine weight, a 60 hp tractor was sufficient to operate this machine. A typical 60 hp tractor has a rear lift capacity of more than 3,000 lb with a category II hitch and a hydraulic capacity of more than 20 gpm at suitable delivery pressure. However, a higher horsepower tractor will have greater specifications than what is required by the machine and will be ideal for operating the harvesting aid. A CASE 125 MAXXUM tractor was used for most of the testing that is rated at 125 hp measured at the PTO. Other factors to consider for the tractor requirements are the tractor needs to have a pressure-flow compensating hydraulic system with a fixed or variable displacement hydraulic pump.

2.3.2. Field evaluation of the two-row vine puller-chopper harvesting aid

Testing with the two-row vine puller-chopper harvesting aid (Figure 2.25) was done in 2016, 2017 and 2018 harvesting seasons. Testing was done primarily at Grantham Farms

(Grantham, NC), Burch Farms (Faison, NC), Rockridge Farms (Wilson, NC) and Tull-Hill Farms (Kinston, NC). The focus for the initial part of the field testing was to improve the performance of the harvesting aid by eliminating material clogging and making minor design improvements to achieve complete vine-root separation. With the two-row vine puller-chopper harvesting aid, row lengths greater than 2500 ft were traversed in a single pass and the harvesting aid performed well in terms of achieving vine-root separation. Once the clogging problems were addressed and continuous operation was achieved, field tests were conducted to find the optimum machine settings of the harvesting aid with respect to the mower rpm, pinch-roller rpm and the ground speed. The two-row vine puller-chopper is shown in a field with the Averre variety (Figure 2.26) during the 2017 harvesting season, one of the hills shows the roots that were separated from the main stem. The performance of the harvesting aid was evaluated in terms of separation efficiency (Smith and Wright, 1994). Separation efficiency for this kind of a harvesting aid which aims to achieve main stem – root separation can be defined as the

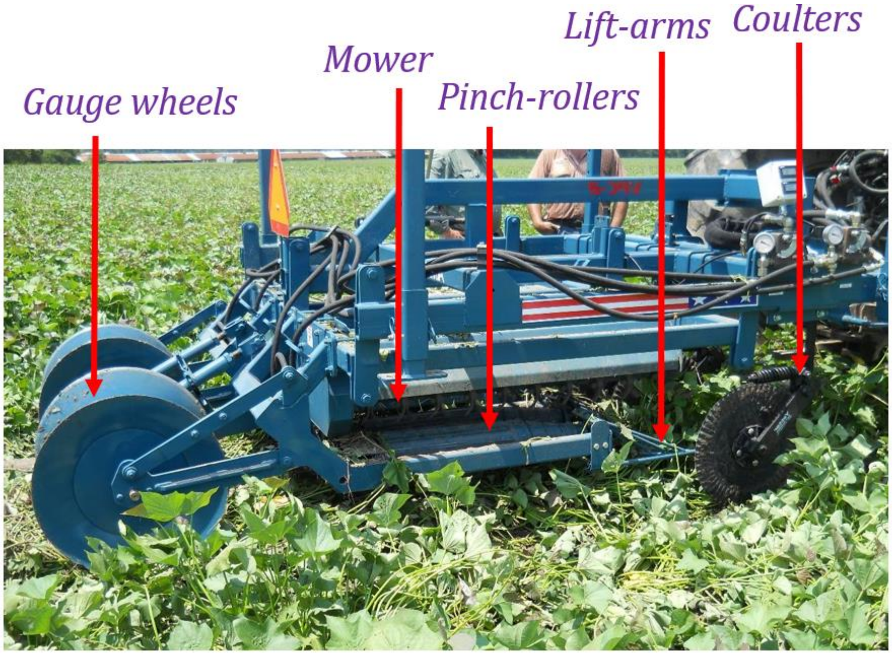

Figure 2.25: Field testing of the two-row vine puller-chopper harvesting aid at Burch Farms, NC in a field with the Covington variety of sweetpotato

percentage of main stems separated from the roots with respect to the total number of main stems (hills) encountered over the distance traveled.

Figure 2.26: The two-row vine puller-chopper in a field with Averre variety of sweetpotato in the 2017 harvesting season (left) with a hill of separated roots (right)

2.4. Results and Discussion

The machine performance was analyzed with four different sweetpotato varieties; Bellevue, Beauregard, Covington and Jewel. The four varieties were used to optimize the machine parameters (settings) including mower rpm, pinch-roller rpm and the ground speed to maximize the performance of the machine in terms of separation efficiency. There was a difference in the machine performance in each variety which can also be attributed to the growth structure and the different nature of the varieties at the time of harvest. We had already achieved the high separation efficiencies with our one-row prototype but a major improvement with the two-row prototype was the continuous machine performance without clogging for row lengths up to 2500 ft. The machine performance did not seem to be affected by soil conditions.

2.4.1. Field evaluation for optimizing machine parameters

Three pinch-roller rpms were considered: 90 rpm, 180 rpm and 280 rpm. Kakahy et al. (2013) achieved maximum performance efficiency of their vine disposal machine with similar rotating cylinders at 300 rpm. It was observed that with roller speeds of more than 300 rpm there were vines being scraped and cut by the pinch-rollers instead of grasping and pulling them. The pinch-rollers' OD was 6 inches. For roller speeds greater than 300 rpm, the peripheral speed (pulling velocity) with which the rollers pulled the vines up was calculated to be greater than 5 mph. This value was in the higher end of the pulling velocity range of 0.7 mph to 7 mph established by Humphries and Abrams (1975) who stated that speeds less than 0.7 mph were likely to pull the sweetpotato hills up instead of separating the main stem from the roots and speeds greater than 7 mph were likely to snap the vines at the point of pull instead of separating the vines from the roots. Speeds above 300 rpm were too high and greatly decreased the performance in terms of separation efficiency. With roller speeds at 90 rpm (equivalent to peripheral speed or pulling velocity of 1.5 mph), it was observed that for the dense, thick vines the rollers would clog and were not able to pull the vines all the time. Therefore only 180 rpm and 280 rpm were considered evaluating the optimum machine parameters.

The three mower speeds considered for testing were 800 rpm, 1200 rpm and 1600 rpm. It was observed for dense, thick vines the mower speeds of 800 rpm would result in the vines being caught up in the mower instead of the mower chopping them and as a result the mower would clog at lower rpms. Therefore, only two mower speeds at 1200 rpm and 1600 rpm were considered. Higher mower speeds were deemed an unnecessary waste of fluid power as there was excessively fine chopping of the vines even for dense, thick vines at 1600 rpm. Tests for four varieties of Beauregard, Covington, Jewel and Bellevue were done over the 2016 and 2017 harvesting seasons and the machine performance was evaluated for row lengths over 100 ft and in some cases up to 800 ft in terms of separation efficiency (Humphries and Abrams, 1975; Smith and Wright, 1994), measured by counting the number of hills with their main stems separated from the roots with respect to the total number of hills encountered over the distance traveled by the harvesting aid, as there were no means to dig the roots. No chain digger was used for these tests, it was only observed from on top of the ground if the main stem had been removed and separated from the roots lying below the soil for each hill. The field conditions were under typical grower practices in North Carolina (Schultheis et al., 1999; Meyers et al., 2010). The vertical pulling force for the fields was noted using a mechanical force gauge (D-200, AMETEK, Largo, FL) with a maximum range of 200 lb. The fields with the Covington variety had an average vertical pulling force of 69.5 lb with a minimum and maximum observed pulling forces of 40 lb and 130 lb, respectively. Beauregard fields had an average vertical pulling force of 53.3 lb with a minimum and maximum observed of 20 lb and 95 lb, respectively. Similarly, the Jewel and Bellevue fields had an average, minimum and maximum pulling forces observed of 64 lb, 45 lb, 100 lb and 58 lb, 15 lb and 90 lb, respectively. The pulling force data for each field and variety gave a descriptive measure of the crop and field conditions associated with the field testing of the harvesting aid. The average vine height observed was approximately 14 inches for Covington and Beauregard, 13 inches for Bellevue and 10 inches for Jewel.

Three ground speeds of 1.4 mph, 2.2 mph and 3 mph were considered for testing with the harvesting aid. These are the ground speeds that were typically achieved at each level of the lowest gear selection (1st gear) of the CASE MAXXUM 125 tractor. Speeds greater than 3 mph were not considered as the machine's performance would decrease drastically at higher speeds. The machine was unable to keep up the performance at higher ground speeds and would miss picking the vines up or clog after traveling short distances. The harvesting aid separation efficiency for the Covington variety at varying combinations of mower, roller and ground speeds is plotted in Figure 2.27. The damage percentage of the harvesting aid was also plotted, which was to depict any kind of damage caused to the roots by the harvesting aid or any of its machine components by skinning or causing abrasions. Sometimes due to the row terrain and growing practices, the positioning of the harvesting aid too close to the surface of the rows may result in the moving components such as the rollers or the gauge wheel scraping the tops of the roots emerging out of the soil or very close to the soil surface. To quantify this effect, the percentage damaged roots (or damage efficiency) was plotted which was measured by counting the number of hills the harvesting aid caused any damage to whether it was a slight scrape (which occurred in most cases) or a deeper cut with respect to the total number of hills encountered over the distance traveled.

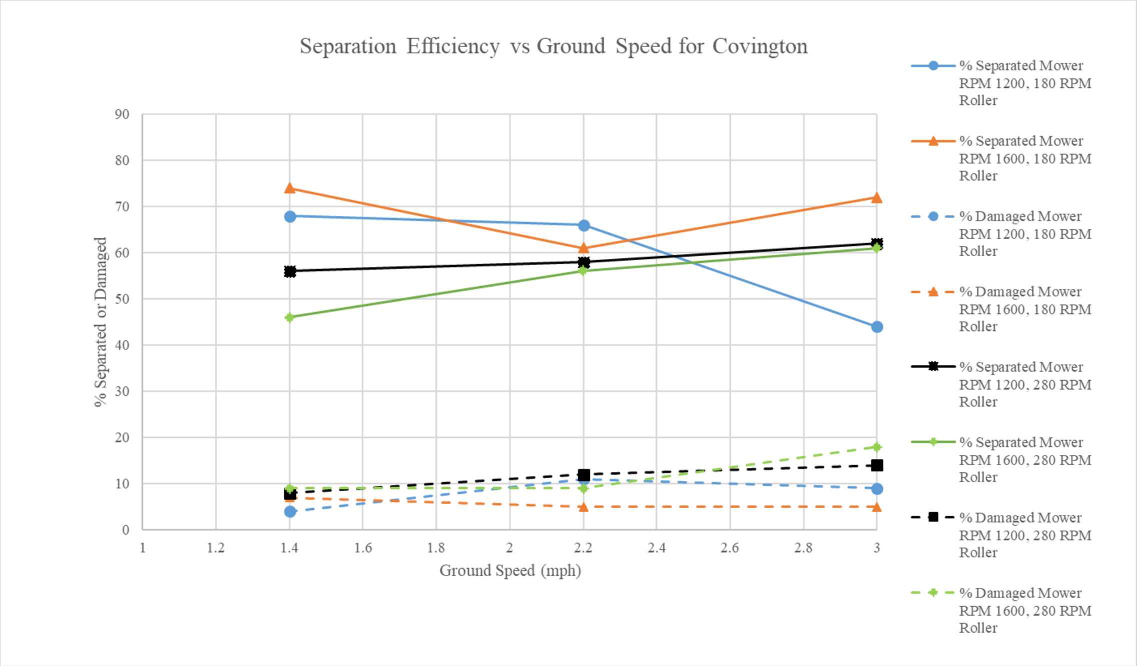

Figure 2.27: Separation efficiency and damage percentage of the harvesting aid for the Covington variety at the three ground speeds for varying mower and roller rpm

A combination of 1.4 mph ground speed, 180 roller rpm and 1600 mower rpm achieved the maximum average separation efficiency of 74% while a ground speed of 3 mph, 1200 mower rpm and 180 roller rpm yielded the minimum average separation efficiency of approximately 44%. The overall damage percentage seemed to increase with ground speed and roller rpm and a maximum of 18% damaged was observed for a combination of 3 mph ground speed, 280 roller rpm and 1600 mower rpm. A higher damage percentage with the harvesting aid occurred with the Covington variety as root tops were sticking out of the soil cover and the rollers and the gauge wheel would damage the roots.

The harvesting aid separation efficiency for the Beauregard variety at varying combinations of mower, roller and ground speeds is plotted in Figure 2.28. A combination of 1.4 mph ground speed, 180 roller rpm and 1600 mower rpm achieved maximum separation efficiency of 81%. The maximum damage percentage was 8% at a ground speed of 2.2 mph for 280 roller rpm and 1600 mower rpm, with damage ranging between 2% and 8%. There was not much difference in the percentage damaged for all the machine parameter combinations, although not consistent over all the settings. Separation efficiency was similar for ground speeds of 2.2 mph and 3 mph with the exception of a combination of 1200 mower rpm and 180 roller rpm at 2.2 mph ground speed where the separation efficiency was observed to be a little higher at 77% compared to the other machine settings (parameters).

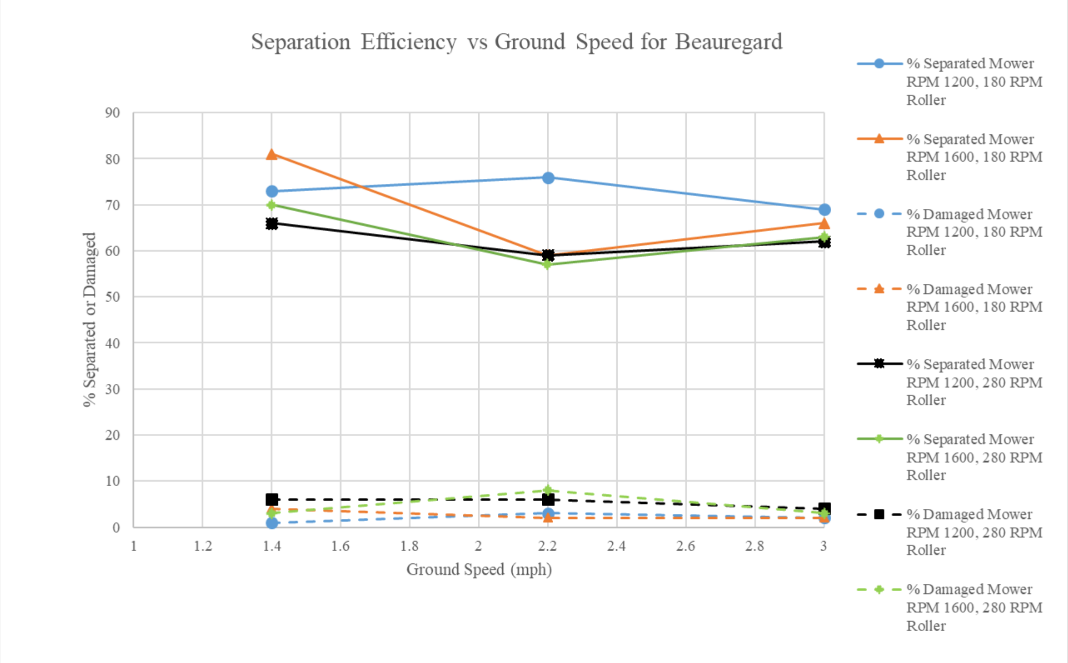

Figure 2.28: Separation efficiency and damage percentage of the harvesting aid for the Beauregard variety at the three ground speeds for varying mower and roller rpm

The harvesting aid separation efficiency for the Jewel variety at varying combinations of mower, roller and ground speeds is plotted in Figure 2.29. There was considerable decrease in the overall separation efficiency numbers for the Jewel variety (average of 26%) compared to the other varieties which averaged more than 60%. This is likely due to the growth structure of the Jewel crop. The Jewel variety does not have a large distinct main stem like the Covington variety. The vine growth pattern of the Jewel variety was observed to be more of a thin network of fibrous branches with vine height of less than 10 inches rather than having a broad thick main stem and having laterals emerge from it. Therefore, it was difficult for the vine puller-chopper harvesting aid to grasp and pull these kind of vines effectively as most of them would slide below the rollers instead of being placed for the mower to chop them. Design changes for the Jewel variety were not made as the harvesting aid was effective for the other varieties. The Jewel variety is grown by very few growers in North Carolina, with the majority cultivars being

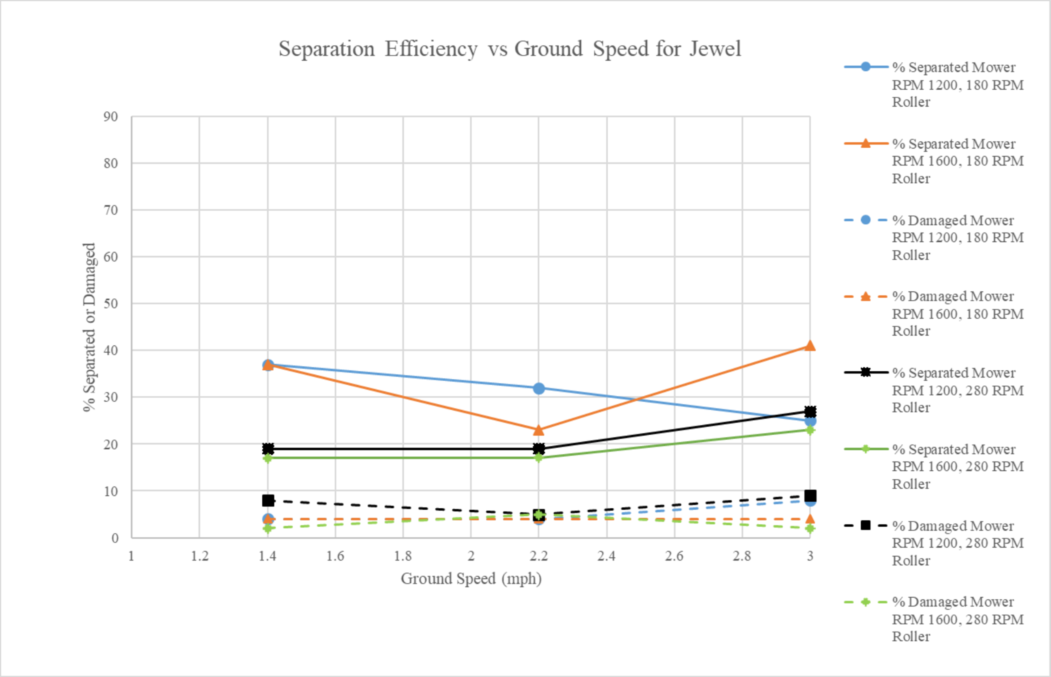

Figure 2.29: Separation efficiency and damage percentage of the harvesting aid for the Jewel variety at the three ground speeds for varying mower and roller rpm

Covington and Beauregard (Yencho et al., 2008; Smith et al., 2009). A maximum separation efficiency of 41% for the Jewel variety was observed for a combination of 3 mph, 180 roller rpm and 1600 mower rpm. The percentage of roots damaged were lower compared to the Covington variety and didn't seem to change much with any changes in the machine parameter combinations with a maximum of 9% for 3 mph ground speed, 280 roller rpm and 1200 mower rpm.

The harvesting aid separation efficiency for the Bellevue variety at varying combinations of mower, roller and ground speeds is plotted in Figure 2.30. The response of the Bellevue variety to the harvesting aid was similar to the Beauregard variety and was likely due to the similarity in the cultivar growth pattern and structure. Maximum separation efficiency of 80% was observed for a combination of 3 mph ground speed, 180 roller rpm and 1200 mower rpm. The maximum damage percentage was 8% at a ground speed of 3 mph, 280 roller rpm and 1200

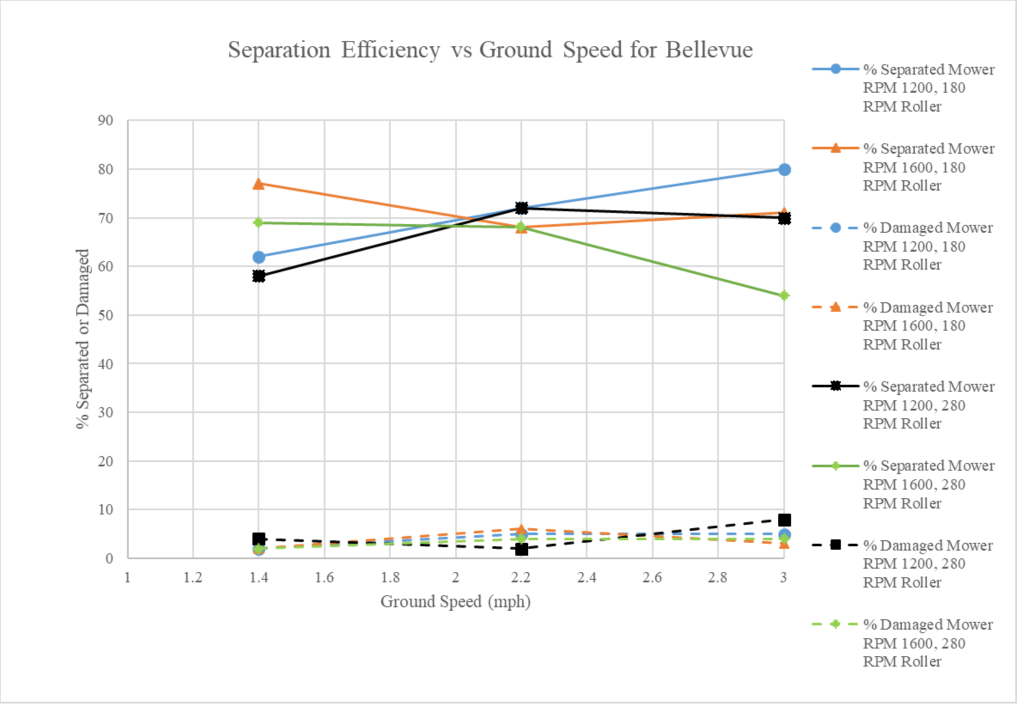

Figure 2.30: Separation efficiency and damage percentage of the harvesting aid for the Bellevue variety at the three ground speeds for varying mower and roller rpm

mower rpm. There was not much difference in the percentage damaged for all the combinations of the machine parameters, although not consistent over all the settings.

The separation efficiency averaged over all ground speeds, mower speeds and roller speeds for the four varieties of Beauregard, Covington and Bellevue were calculated and plotted in Figure 2.31 and provide an indication of the performance of the harvesting aid, irrespective of the soil, field, and machine parameters. The average separation efficiency was lowest for the Jewel variety at approximately 27% and highest for the Bellevue variety at 68.42%. The average separation efficiency for the Covington and the Beauregard varieties was 60.33% and 66.75%, respectively. The average damage percentage was higher for Covington (9.25%) compared to other varieties of Beauregard (3.67%), Bellevue (3.92%) and Jewel (4.92%) as the Covington root tops were sticking out of the soil cover in most fields and the rollers or the gauge wheel would damage the roots. In most of the field tests, a roller speed of 180 rpm achieved more separation efficiency compared to 280 rpm.

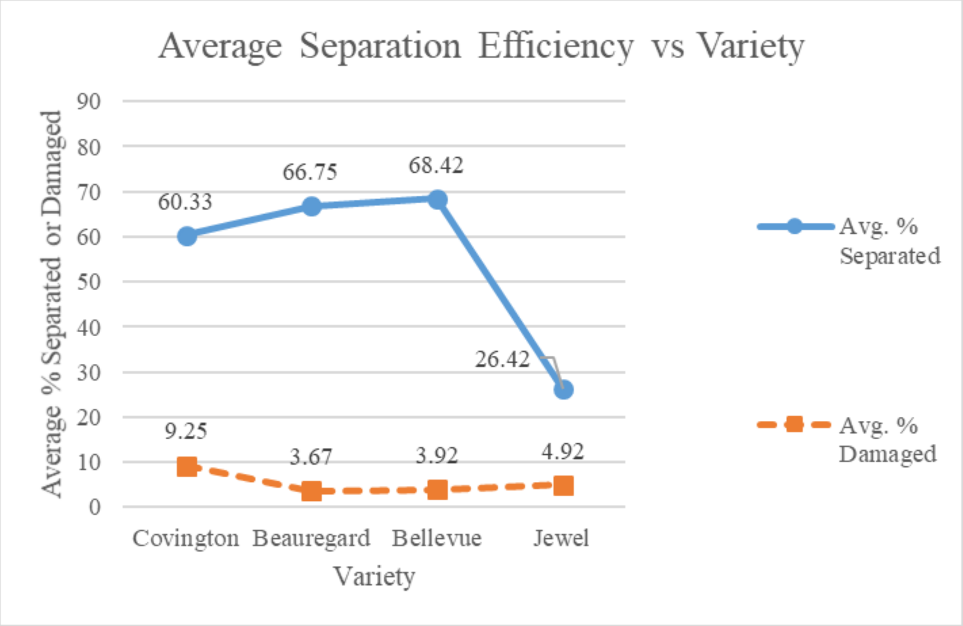

Figure 2.31: Average separation efficiency and damage percentage for Covington, Beauregard, Bellevue and Jewel varieties, averaged over all ground speeds, mower and roller rpm

The separation efficiency and damage percentage were averaged for each variety over all ground speeds and mower speeds and plotted in Figure 2.32. The separation efficiency numbers were, on average, higher for each variety by at least 7% when the machine was operated at a roller speed of 180 rpm compared to 280 rpm with the difference being more than 12% for Jewel variety. This response may be because higher roller speeds sometimes scrape and cut the vines instead of grasping and pulling them (Humphries and Abrams, 1975). For roller speeds of 180 rpm and 280 rpm, the peripheral speed (or pulling velocity) with which the pinch-rollers pulled the vines was calculated to be approximately 3 mph and 4.7 mph, respectively. Humphries and Abrams (1975) established a pulling velocity range of 0.7 mph to 7 mph for sweetpotatoes with the higher speeds more likely to scrape and cut the vines and the lower speeds more likely to pull the entire hill above the ground instead of grasping and pulling them to achieve vine-root separation. As the pulling velocity obtained for the roller speed of 280 rpm was higher, it was

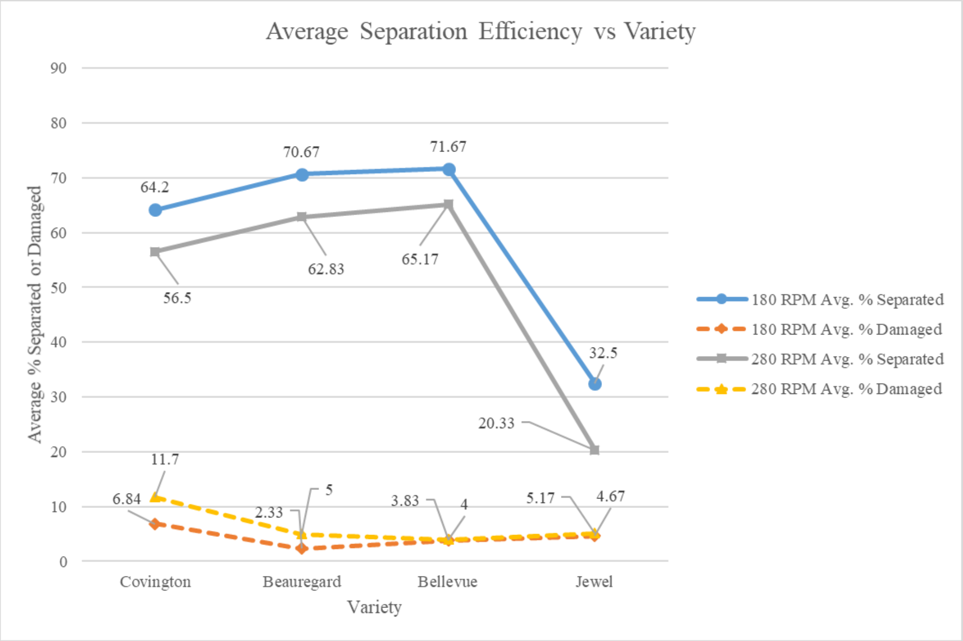

Figure 2.32: Average separation efficiency and damage percentage for Covington, Beauregard, Bellevue and Jewel varieties at roller speeds of 180 rpm and 280 rpm, averaged over all ground speeds and mower rpm

more likely that this roller speed cut the vines instead of grasping and pulling them to achieve vine-root separation compared to the roller speed of 180 rpm. The percentage of damaged roots was higher for Covington and Beauregard at 280 rpm on average whereas treatment response was similar irrespective of the roller rpm for Bellevue and Jewel varieties.

Similarly, the separation efficiency and damage percentage were averaged for each variety over all ground speeds and roller speeds and plotted in Figure 2.33 to compare the machine performance at 1200 and 1600 mower rpm. The average separation efficiency was similar at mower speeds of 1200 rpm compared to 1600 rpm for each variety. The average percentage damaged was also similar for both the mower speeds for each variety. Operating the mower at 1600 rpm consumed more fluid power than operating it at 1200 rpm. The 1600 rpm of the mower was an unnecessary waste of fluid power compared to 1200 rpm as there was excessively fine chopping of the vines in most cases.

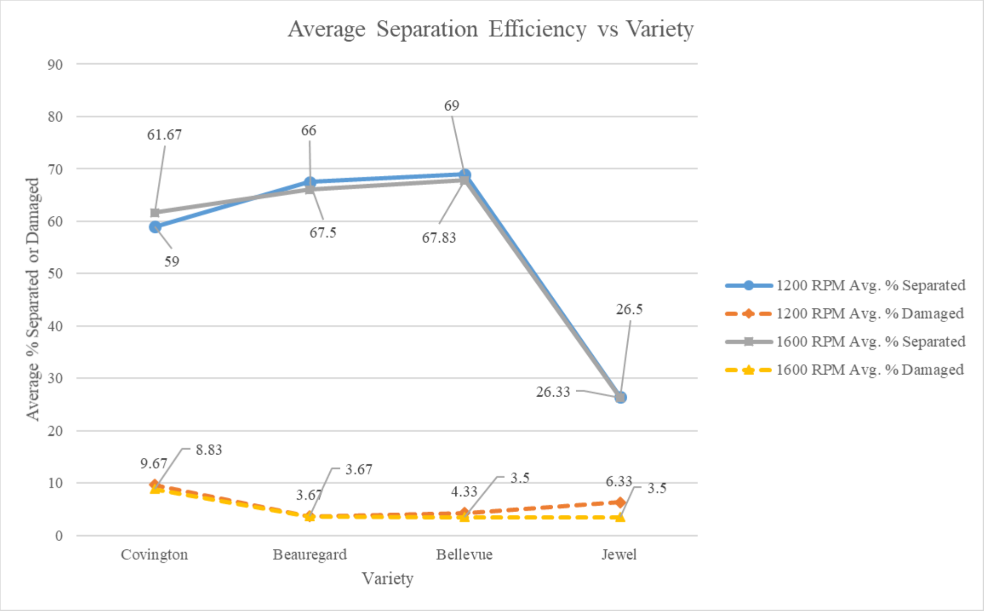

Figure 2.33: Average separation efficiency and damage percentage for Covington, Beauregard, Bellevue and Jewel varieties at mower speeds of 1200 rpm and 1600 rpm, averaged over all ground speeds and pinch-roller rpm

The separation efficiency and damage percentage at ground speeds of 1.4, 2.2 and 3 mph averaged over all mower speeds and roller speeds for the four varieties of Beauregard, Covington, Bellevue and Jewel are presented in Figure 2.34. The average separation efficiency was approximately 60% for all 3 speeds for the Covington variety. For the Beauregard variety 1.4 mph had the highest average separation efficiency of 72.5% whereas 3 mph had 65% and 2.2 mph had 62.75%. For the Bellevue variety 2.2 mph achieved maximum average separation efficiency of 70% with 3 mph achieving 68.75 % and 1.4 mph with 66.5%. For Jewel variety it was observed that 3 mph had highest average separation efficiency of 29% with 1.4 mph at 27.5% and 2.2 mph having 22.75% average separation efficiency. The differences in damage percentage seemed minimal (< 3%) for the three ground speeds for Beauregard, Bellevue and Jewel varieties. The Covington variety had a maximum average damage percentage of 11.5% at 3 mph ground speed and a minimum average damage percentage of 7% at 1.4 mph ground speed

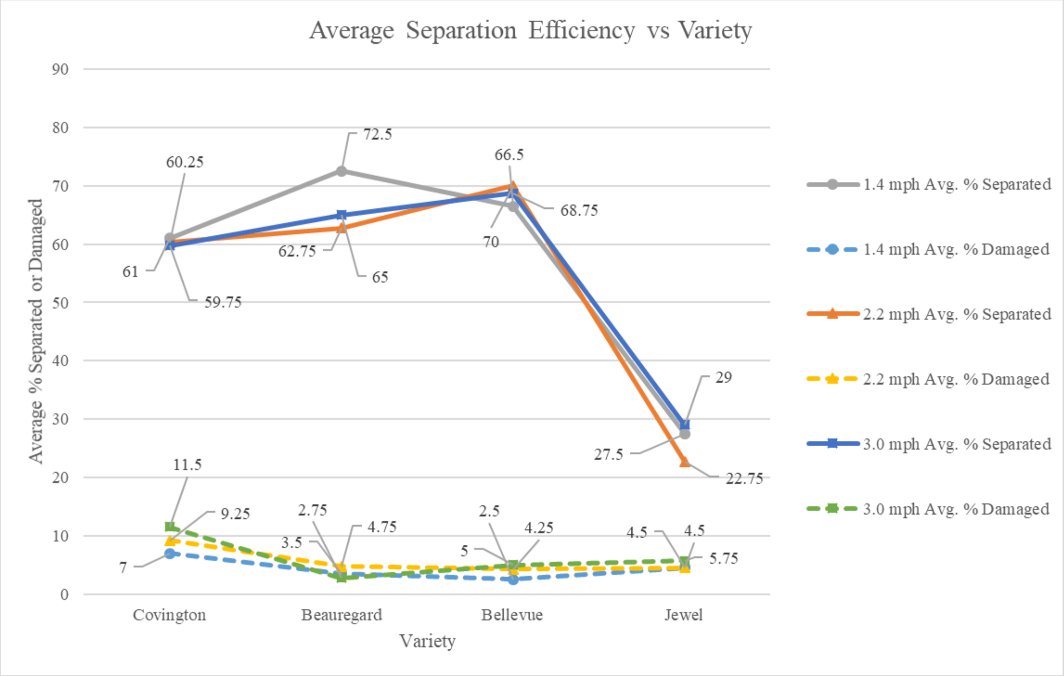

Figure 2.34: Average separation efficiency and damage percentage for Covington, Beauregard, Bellevue and Jewel varieties at ground speeds of 1.4 mph, 2.2 mph and 3 mph, averaged over all roller and mower rpm

which was more than the maximum damage percentage calculated for the other three varieties. As already mentioned, this was due to the Covington root tops sticking out of the soil in most cases and being damaged by the rollers and the gauge wheel. The separation efficiency and damage percentage data for all the varieties at varying roller, mower and ground speeds is shown in Table 2.1.

Table 2.1: Separation efficiency and percentage roots damaged data for Covington, Beauregard, Jewel and Bellevue varieties at varying roller, mower and ground speeds

Variety	Ground Speed (mph)	Roller rpm	Mower rpm	% Separated	% Damaged
Covington	1.4	180	1200	68	4
Covington	2.2	180	1200	66	11
Covington	3	180	1200	44	9
Covington	1.4	180	1600	74	7
Covington	2.2	180	1600	61	5
Covington	3	180	1600	72	5
Covington	1.4	280	1200	56	8
Covington	2.2	280	1200	58	12
Covington	3	280	1200	62	14
Covington	1.4	280	1600	46	9
Covington	2.2	280	1600	56	9
Covington	3	280	1600	61	18
Beauregard	1.4	180	1200	73	1
Beauregard	2.2	180	1200	76	3
Beauregard	3	180	1200	69	2
Beauregard	1.4	180	1600	81	4
Beauregard	2.2	180	1600	59	2
Beauregard	3	180	1600	66	2
Beauregard	1.4	280	1200	66	6
Beauregard	2.2	280	1200	59	6
Beauregard	3	280	1200	62	4
Beauregard	1.4	280	1600	70	3
Beauregard	2.2	280	1600	57	8
Beauregard	3	280	1600	63	3
Jewel	1.4	180	1200	37	4
Jewel	2.2	180	1200	32	4
Jewel	3	180	1200	25	8

Table 2.1 (continued)

Variety	Ground Speed (mph)	Roller rpm	Mower rpm	% Separated	% Damaged
Jewel	1.4	180	1600	37	4
Jewel	2.2	180	1600	23	4
Jewel	3	180	1600	41	4
Jewel	1.4	280	1200	19	8
Jewel	2.2	280	1200	19	5
Jewel	3	280	1200	27	9
Jewel	1.4	280	1600	17	2
Jewel	2.2	280	1600	17	5
Jewel	3	280	1600	23	2
Bellevue	1.4	180	1200	62	2
Bellevue	2.2	180	1200	72	5
Bellevue	3	180	1200	80	5
Bellevue	1.4	180	1600	77	2
Bellevue	2.2	180	1600	68	6
Bellevue	3	180	1600	71	3
Bellevue	1.4	280	1200	58	4
Bellevue	2.2	280	1200	72	2
Bellevue	3	280	1200	70	8
Bellevue	1.4	280	1600	69	2
Bellevue	2.2	280	1600	68	4
Bellevue	3	280	1600	54	4

A general linear model (GLM) was used in SAS software (SAS Institute, 2017) to investigate the factorial effects with 2nd order interactions of all four factors of variety, ground speed, roller and mower speeds for the separation efficiency and damage percentage as response variables. For separation efficiency as the response variable, the normality assumption did not hold. Thus, a logarithmic transformation of the average separation efficiency was used in the model. The analysis of variance (ANOVA) shown in Table 2.2 had an R-square value of 0.99. A test of equality of separation efficiency across all treatment combinations was rejected (p-value = 0.0003). The assumptions for constant variance and normality were checked using diagnostic plots generated by SAS. Each sweetpotato hill can be considered as independent from the other hills. A residuals vs predicted values was plotted (see Appendix A, Figure S1) to check for non-constant variance and a quantile-quantile plot (see Appendix A, Figure S1) was inspected to see if the normality assumption was reasonable.

Table 2.2: ANOVA of linear model with the log transformed separation efficiency as response with factorial effects of variety, ground speed, mower and roller speed

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	41	1.8174	0.0443	26.14	0.0003
Error	6	0.0101	0.0016		
Corrected Total	47	1.8276			

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Variety	3	1.5204	0.5068	298.87	<.0001
Ground Speed	2	0.0073	0.0036	2.16	0.1962
Variety*Ground Speed	6	0.0263	0.0043	2.59	0.1359
Roller	1	0.0885	0.0885	52.23	0.0004
Variety*Roller	3	0.0525	0.0175	10.34	0.0087
Ground Speed*Roller	2	0.0172	0.0086	5.09	0.0510
Variety*Ground Speed*Roller	6	0.0257	0.0042	2.53	0.1418
Mower	1	0.0001	0.0001	0.12	0.7444
Variety*Mower	3	0.0020	0.0006	0.41	0.7537
Ground Speed*Mower	2	0.0138	0.0069	4.07	0.0764
Variety*Ground Speed*Mower	6	0.0306	0.0051	3.01	0.1028
Roller*Mower	1	0.0060	0.0060	3.58	0.1074
Variety*Roller*Mower	3	0.0087	0.0029	1.73	0.2605
Ground Speed*Roller*Mower	2	0.0176	0.0088	5.19	0.0491

The observed variation among varieties (p-value < 0.0001), roller speeds (p-value = 0.0004), their interaction (p-value = 0.0087), along with the 2nd order interaction of the ground speed, roller and mower speeds (p-value = 0.049) were significant. The least square means (lsmeans) for the ground speed, roller and mower speed interaction were plotted in Figure 2.35.

The tests for simple effects of the roller speed and mower speed are shown in Table 2.3 and Table 2.4, respectively.

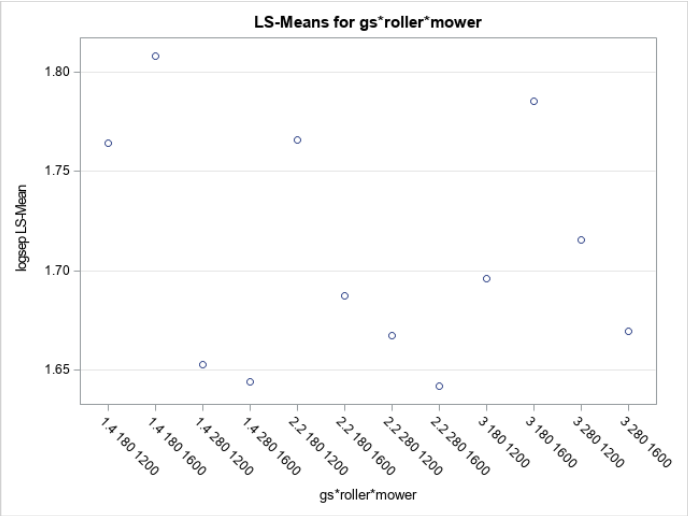

Figure 2.35: Least square means plot for the ground speed, mower and roller speed interaction

The roller speed effect on log transformed separation efficiency was negative for all ground speed, mower speed combinations except for 3 mph, 1200 rpm. The mower speed effect on log transformed separation efficiency was not significant for 280 roller rpm and positive for 180 roller rpm at ground speeds of 1.4 mph and 3 mph.

Table 2.3: Tests for simple effects of roller speed at combinations of mower and ground speeds for log transformed separation efficiency as response (Ground Speed*Roller*Mower effect sliced by Ground Speed*Mower)

Ground Speed	Mower	DF	Sum of Squares	Mean Square	F Value	Pr > F
1.4	**1200**	1	0.0249	0.0249	14.70	0.0086
1.4	**1600**	1	0.0536	0.0536	31.65	0.0013
2.2	**1200**	1	0.0192	0.0192	11.35	0.0150
2.2	**1600**	1	0.0042	0.0042	2.48	0.1664
3	**1200**	1	0.0007	0.0007	0.45	0.5284
3	**1600**	1	0.0266	0.0266	15.74	0.0074

Table 2.4: Tests for simple effects of mower speed at combinations of roller and ground speeds for log transformed separation efficiency as response (Ground Speed*Roller*Mower effect sliced by Ground Speed*Roller)

Ground Speed	Roller	DF	Sum of Squares	Mean Square	F Value	Pr > F
1.4	**180**	1	0.0038	0.0038	2.28	0.1816
1.4	**280**	1	0.0001	0.0001	0.08	0.7880
2.2	**180**	1	0.0122	0.0122	7.19	0.0364
2.2	**280**	1	0.0013	0.0013	0.79	0.4091
3	**180**	1	0.0159	0.0159	9.43	0.0219
3	**280**	1	0.0041	0.0041	2.45	0.1683

Similar analysis was carried out with the damage percentage as the response variable. A general linear model (GLM) was used in SAS software to investigate the factorial effects with 2nd order interactions of all four factors of variety, ground speed, roller and mower speeds for damage percentage as the response variable. The ANOVA (Table 2.5) had an R-square value of 0.98. A test of equality of percentage damaged across all treatment combinations was rejected (p-value = 0.0078). The assumptions for constant variance and normality were checked using diagnostic plots generated by SAS. Each sweetpotato hill can be considered as independent from other hills. A residuals vs predicted values was plotted (see Appendix A, Figure S2) to check for non-constant variance and a quantile-quantile plot (see Appendix A, Figure S2) was inspected to see if the normality assumption was reasonable.

The variety had a significant effect on the damage percentage and was maximum for Covington as observed previously. The observed variation among varieties (p-value = 0.0001), roller speeds (p-value = 0.0017), their interaction (p-value = 0.015), ground speeds (p-value = 0.017), mower speeds (p-value = 0.025), along with interaction of the ground speed, roller and mower (p-value = 0.047) were significant.

Table 2.5: ANOVA of linear model for the percentage damaged as response with factorial effects of variety, ground speed, mower and roller speed

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	41	555.437	13.547	7.83	0.0078
Error	6	10.375	1.729		
Corrected Total	47	565.812			

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Variety	3	243.062	81.020	46.86	0.0001
Ground Speed	2	29.625	14.812	8.57	0.0174
Variety*Ground Speed	6	36.375	6.062	3.51	0.0761
Roller	1	50.020	50.020	28.93	0.0017
Variety*Roller	3	42.229	14.076	8.14	0.0155
Ground Speed*Roller	2	5.791	2.895	1.67	0.2643
Variety*Ground Speed*Roller	6	38.208	6.368	3.68	0.0689
Mower	1	15.187	15.187	8.78	0.0252
Variety*Mower	3	13.062	4.354	2.52	0.1548
Ground Speed*Mower	2	7.625	3.812	2.20	0.1915
Variety*Ground Speed*Mower	6	40.375	6.729	3.89	0.0614
Roller*Mower	1	1.020	1.020	0.59	0.4714
Variety*Roller*Mower	3	14.562	4.854	2.81	0.1304
Ground Speed*Roller*Mower	2	18.291	9.145	5.29	0.0474

The least square means (lsmeans) for the ground speed, roller and mower speed interaction were plotted in Figure 2.36. The tests for simple effects of the roller and mower speed are shown in Table 2.6 and Table 2.7, respectively. The roller speed effect on the damage percentage was significant for a ground speed of 3 mph, and negative for all ground speed, mower speed combinations except for 1.4 mph, 1600 rpm. The mower speed effect on the damage percentage was significant for a ground speed of 3 mph, and negative for all ground speed, roller speed combinations except for 1.4 mph, 180 rpm and 2.2 mph, 280 rpm.

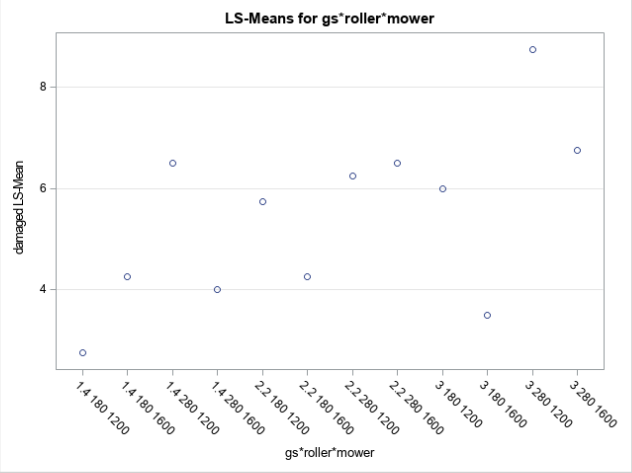

Figure 2.36: Least square means plot for the ground speed, mower and roller speed interaction

Table 2.6: Tests for simple effects of roller speed at combinations of mower and ground speeds for percentage damaged as response (Ground Speed*Roller*Mower effect sliced by Ground Speed*Mower)

Ground Speed	Mower	DF	Sum of Squares	Mean Square	F Value	Pr > F
1.4	**1200**	1	28.1250	28.1250	16.27	0.0069
1.4	**1600**	1	0.1250	0.1250	0.07	0.7970
2.2	**1200**	1	0.5000	0.5000	0.29	0.6101
2.2	**1600**	1	10.1250	10.1250	5.86	0.0519
3	**1200**	1	15.1250	15.1250	8.75	0.0254
3	**1600**	1	21.1250	21.1250	12.22	0.0129

Table 2.7: Tests for simple effects of mower speed at combinations of roller and ground speeds for percentage damaged as response (Ground Speed*Roller*Mower effect sliced by Ground Speed*Roller)

Ground Speed	Roller	DF	Sum of Squares	Mean Square	F Value	Pr > F
1.4	**180**	1	4.5000	4.5000	2.60	0.1578
1.4	**280**	1	12.5000	12.5000	7.23	0.0361
2.2	**180**	1	4.5000	4.5000	2.60	0.1578
2.2	**280**	1	0.1250	0.1250	0.07	0.7970
3	**180**	1	12.5000	12.5000	7.23	0.0361
3	**280**	1	8.0000	8.0000	4.63	0.0750

From the field test observations and the analyses, operating the roller at 180 rpm was best suited for the vine puller-chopper harvesting aid compared to 280 rpm. The roller speed of 180 rpm resulted in higher average separation efficiency compared to 280 rpm for all the varieties and the roller speed effect on the log transformed separation efficiency and damage percentage was negative for all ground speed, mower combinations except 3 mph, 1200 rpm and 1.4 mph, 1600 rpm, respectively. A mower speed of 1200 rpm was considered optimum for the harvesting aid based on the field test observations and the analyses. The mower speed effect on the damage percentage was significant for a ground speed of 3 mph, and negative for all combinations of ground speed, roller speed combinations except for 1.4 mph, 180 rpm and 2.2 mph, 280 rpm. The mower speed effect on log transformed separation efficiency was not significant for 280 roller rpm and positive for 180 roller rpm at ground speeds of 1.4 mph and 3 mph. Operating the mower at 1600 rpm consumed more fluid power and caused excessively fine chopping of the vine material in most cases compared to 1200 rpm which was not necessary and deemed a waste of fluid power. Thus, roller speed of 180 rpm and mower speed of 1200 rpm were considered as optimum machine parameters for the vine puller-chopper harvesting aid.

The above field tests were conducted for different row lengths (100 ft to 800 ft) and by counting the main stems from the roots from above as there was no means of digging but was sufficient to optimize the mower and roller rpm for optimum machine performance. The most important external parameter for the grower in assessing a harvesting aid is the ground speed and acreage covered as harvesting is time sensitive and the grower needs to cover large areas within a small amount of time. The internal machine parameters such as the mower rpm and roller rpm do not really matter to the grower as long as the machine is doing its job. However, a change from

1.4 mph to 3 mph ground speed of the harvesting aid would result in a given acreage being covered in less than half the time.

Field tests were also carried out at the various ground speeds achieved by the vine puller-chopper harvesting aid for fixed row lengths at optimum established machine parameters with a chain digger used for digging and counting the separation efficiency of the number of roots separated in a hill and averaged over the row lengths. For these tests of fixed row lengths at optimum machine parameters, separation efficiency, an indicator of the machine performance, was assessed along with the damaged percentage of the roots at the various ground speeds achieved by the harvesting aid. It was also important to determine if the harvesting aid's performance, through these tests, was sensitive to crop variety and field conditions such as soil moisture or soil temperature (Smith and Wright, 1994).

It was already established that optimum speeds for the pinch-rollers and the mower were 180 rpm and 1200 rpm, respectively. To compare the statistical significance of the ground speed on the separation efficiency and damage percentage of the roots by the harvesting aid, three fields of Covington, Beauregard and Averre varieties were available for testing near Faison and Newton Grove, NC. The commercial crop in each field was commercially produced using standard grower practices (Schultheis et al., 1999; Meyers et al., 2010). The force required to pull the vines vertically were noted for each field using a mechanical force gauge (D-200, AMETEK, Largo, FL) with a maximum range of 200 lb. The average pulling force for the Covington, Beauregard and Averre main stem-root separation across the three fields was 70 lb, 53.3 lb and 65 lb, respectively. The pulling force data for each field and variety gave a descriptive measure of the crop and field conditions associated with the field testing of the harvesting aid. The average vine height observed was approximately 14 inches for Covington and Beauregard, and 13 inches for Averre.

2.4.2. Field evaluation for separation efficiency at different speeds using a chain digger

Twelve rows 250 ft long were randomly selected from each field and the vine puller-chopper harvesting aid was operated at 1200 mower rpm and 180 roller rpm throughout the testing. Four rows each were randomly assigned ground speeds of 1.4 mph, 2.2 mph and 3 mph and the vine puller-chopper harvesting aid was operated at the respective ground speeds for the assigned rows. A chain digger (Figure 2.37) was used to dig the roots for each row and the percentage separation efficiency (Humphries and Abrams, 1975; Smith and Wright, 1994), measured as the number of roots separated from the main stem in a hill divided by the total number of roots in the hill averaged over the number of hills encountered by the harvesting aid over the distance traveled, was calculated for each row. The percentage of the roots damaged (or damage efficiency) was measured by counting the number of roots in a hill that were damaged by the harvesting aid, whether it was a slight scrape (which occurred in most cases) or a deeper cut, divided by the total number of roots in a hill and averaged over the number of hills encountered over the distance traveled for each row.

The soil moisture and the soil temperature were recorded for each row of the three fields using a HOBO micro station data logger (H21-002, Onset Computer Corporation, Bourne, MA) with the soil moisture smart sensor (S-SMD-M005, Onset Computer Corporation, Bourne, MA) at the time the harvesting aid was operated. The soil moisture and soil temperature were measured at a constant depth of 6 inches below the soil surface at two random locations in each row. The recorded soil moisture and soil temperature were considered to be a representation of the entire row. The soil moisture and soil temperature were recorded as they can be considered variables that may influence the machine performance (Smith and Wright, 1994). The data collected for each row is tabulated in Table 2.8.

Figure 2.37: Chain digger (left) placing the roots on top of the soil (right) for the rows operated with the harvesting aid

The average separation efficiency and damage percentage for the Beauregard variety was plotted against the machine ground speed in Figure 2.38. The average separation efficiency was

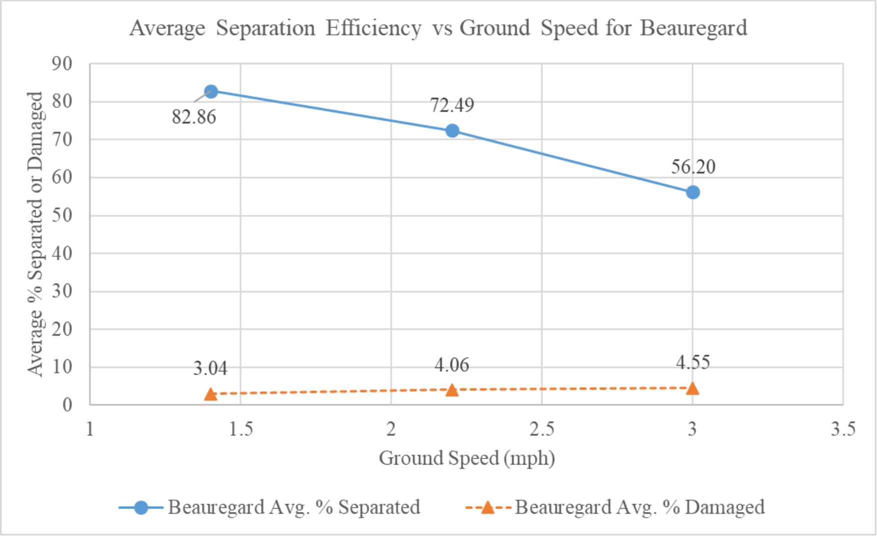

Figure 2.38: Average separation efficiency and damage percentage plots for the Beauregard variety at the three harvesting aid ground speeds of 1.4, 2.2 and 3 mph

Table 2.8: Average separation efficiency and percentage damaged for the three fields with respect to variety, ground speed and the recorded soil moisture, soil temperature

Variety	Ground Speed (mph)	% Separated	% Damaged	Soil Moisture (in^3 in^{-3})	Soil Temperature (°F)
Averre	1.4	80.86	1.97	0.122	59.3
Averre	1.4	81.02	6.26	0.122	59.3
Averre	1.4	74.72	3.71	0.11	60.7
Averre	1.4	72.87	1.66	0.11	60.7
Averre	2.2	77	1.24	0.128	58.7
Averre	2.2	85.35	2.19	0.128	58.7
Averre	2.2	63.22	1.65	0.119	59.3
Averre	2.2	69.38	4.12	0.119	59.3
Averre	3	69.38	1.87	0.125	61
Averre	3	70.64	3.41	0.125	61
Averre	3	73.98	6.6	0.122	59.3
Averre	3	59.87	5.99	0.122	59.3
Covington	1.4	81.1	9	0.239	72.7
Covington	1.4	77.5	3.5	0.239	72.7
Covington	1.4	58.75	5.8	0.243	71.8
Covington	1.4	83.9	12.1	0.243	71.8
Covington	2.2	75.3	2.19	0.233	72.8
Covington	2.2	68.1	8.95	0.233	72.8
Covington	2.2	72.85	8.4	0.235	72.6
Covington	2.2	62.45	8.37	0.235	72.6
Covington	3	45.55	14.1	0.241	72.7
Covington	3	60.68	5.5	0.241	72.7
Covington	3	51.3	7.77	0.24	72.7
Covington	3	68	11.9	0.24	72.7
Beauregard	1.4	89.5	0.85	0.293	70.8
Beauregard	1.4	85.8	6.5	0.293	70.8
Beauregard	1.4	76.8	1.59	0.285	69.92
Beauregard	1.4	79.35	3.2	0.285	69.92
Beauregard	2.2	74	1.88	0.289	69.99
Beauregard	2.2	65.05	5.81	0.289	69.99
Beauregard	2.2	81.12	6	0.285	69.92
Beauregard	2.2	69.8	2.56	0.285	69.92
Beauregard	3	71.7	7.89	0.29	70.2
Beauregard	3	55	5.66	0.29	70.2
Beauregard	3	63.1	2.05	0.285	69.92
Beauregard	3	35	2.6	0.285	69.92

reduced from 82.86% to 56.2% as the ground speed was increased from 1.4 mph to 3 mph. The damage percentage increased slightly from 3.04% at 1.4 mph, to 4.06% for 2.2 mph and 4.55% for 3 mph ground speed.

The average separation efficiency and damage percentage for the Covington variety was plotted against the machine ground speed in Figure 2.39. The average separation efficiency was reduced from 75.31% to 56.38 % as the ground speed was increased from 1.4 mph to 3 mph with the separation efficiency being 69.68% for a ground speed of 2.2 mph. The damage percentage was similar for 1.4 mph and 2.2 mph, but increased to 9.82% as the harvesting aid ground speed was increased to 3 mph.

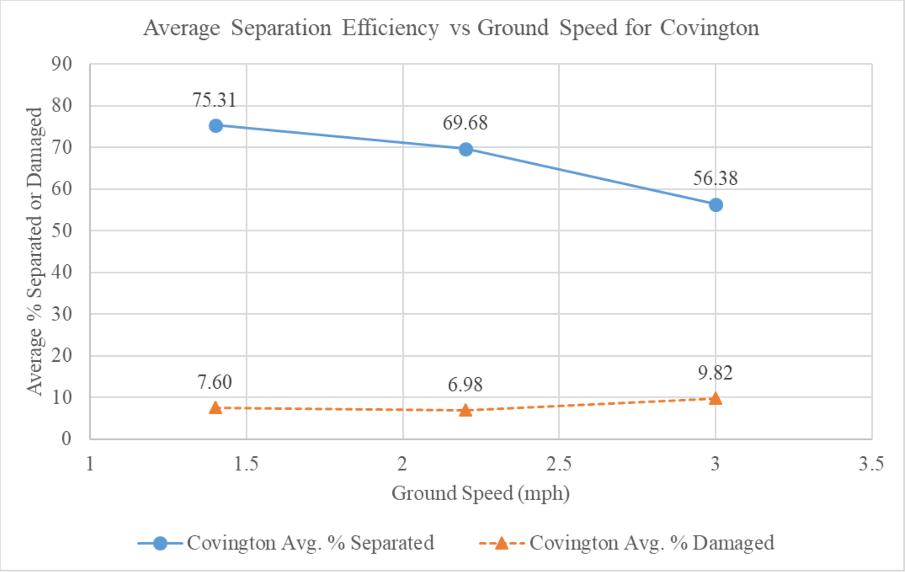

Figure 2.39: Average separation efficiency and damage percentage plots for the Covington variety at the three harvesting aid ground speeds of 1.4, 2.2 and 3 mph

The average separation efficiency and damage percentage for the Averre variety was plotted against the machine ground speed in Figure 2.40. As with the other varieties, the average separation efficiency for the Averre variety was reduced from 77.37% to 68.47% as the ground speed was increased from 1.4 mph to 3 mph. The damage percentage ranged from 2.3% to 4.5% across the different harvesting aid ground speeds.

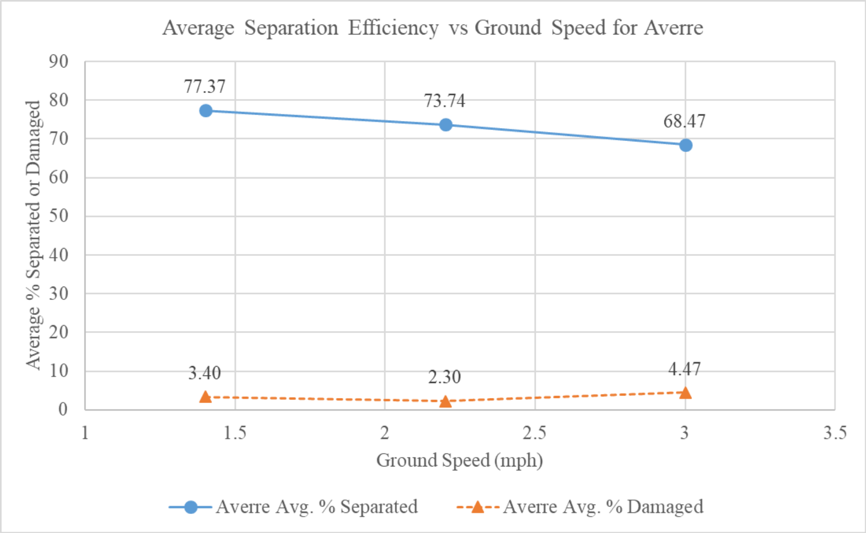

Figure 2.40: Average separation efficiency and damage percentage plots for the Averre variety at the three harvesting aid ground speeds of 1.4, 2.2 and 3 mph

The separation efficiencies averaged over the three varieties at various ground speeds achieved by the harvesting aid are plotted together in Figure 2.41 for comparison. There was an overall decrease in the percentage separated roots with an increase in the harvesting aid ground speed for all varieties. This was also observed during the field tests where the machine was unable to keep up the performance at higher ground speeds and would miss picking some of the vines up due to excessive speeds.

The average percentage of the roots damaged for the three varieties with respect to the ground speed of the harvesting aid are plotted in Figure 2.42 for comparison. The average damaged roots percentage decreased when moving from 1.4 mph to 2.2 mph for Averre and Covington varieties and then increased when running at 3 mph. The damage percentage was more or less steady for the Beauregard variety at the three ground speeds. Higher ground speeds may damage the roots more easily due to the instability of the machine. Lower ground speeds may accumulate and drag the vines below the machine which may also cause damage to the

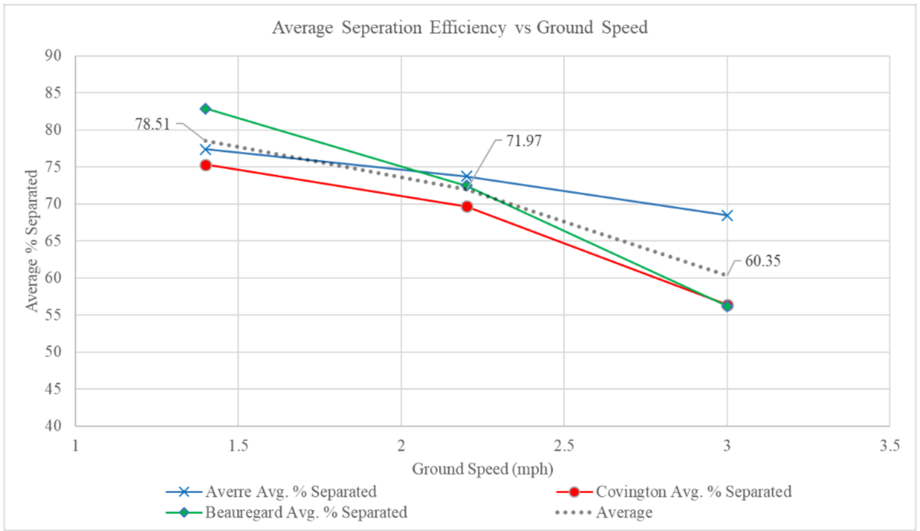

Figure 2.41: Average separation efficiency for Averre, Covington and Beauregard varieties plotted at the three harvesting aid ground speeds of 1.4, 2.2 and 3 mph

roots. As already observed in several of the tests, the Covington variety had more percentage of roots damaged compared to the other varieties.

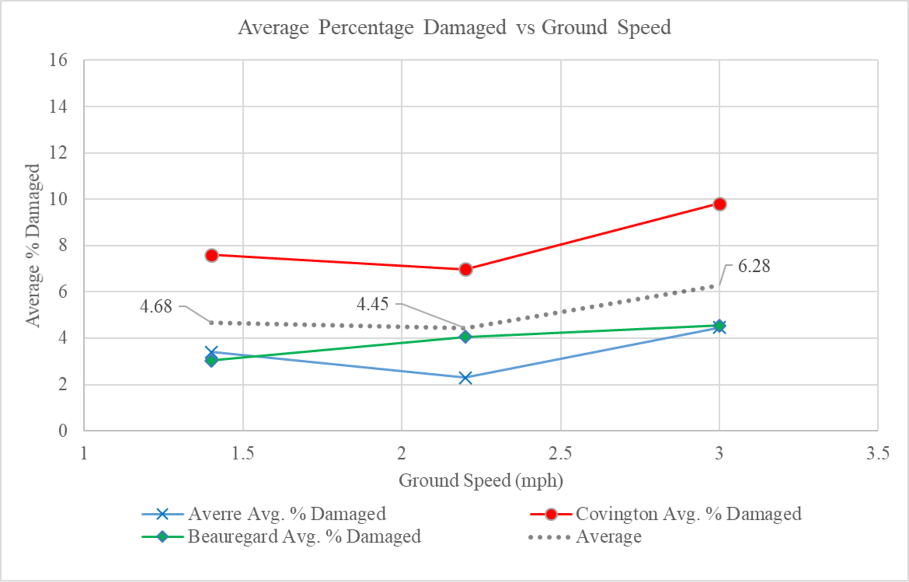

Figure 2.42: Average percentage roots damaged for Averre, Covington and Beauregard varieties plotted at the three harvesting aid ground speeds of 1.4, 2.2 and 3 mph

The separation efficiency data from Table 2.8 were analyzed using linear models fit using the GLM procedure of SAS software. Separation efficiency and damage percentage were considered as the response variables. Variety (Beauregard, Covington and Averre) and ground speed (1.4 mph, 2.2 mph and 3 mph) were the considered factors. The model included fixed factorial effects for variety, ground speed and their interaction. The measured soil temperature (°F), and soil moisture ($in^3\ in^{-3}$) were included as covariates in the model. Models with higher order interactions did not reveal any significant effects and were not considered further. The ANOVA (Table 2.9) for the model with separation efficiency as the response variable had an R-square value of 0.6. A test of equality of separation efficiency across all treatment combinations was rejected (p-value = 0.0032).

Table 2.9: ANOVA of linear model for the separation efficiency as response

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	10	2888.1595	288.8159	3.82	0.0032
Error	25	1891.8519	75.6740		
Corrected Total	35	4780.0114			

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Variety	2	221.9313	110.9656	1.47	0.2499
Ground Speed	2	2031.0822	1015.5411	13.42	0.0001
Soil Moisture	1	306.0382	306.0382	4.04	0.0552
Soil Temperature	1	185.3343	185.3343	2.45	0.1302
Variety*Ground Speed	4	143.7733	35.9433	0.47	0.7537

The observed variation of separation efficiency across the three ground speeds was highly significant (p-value = 0.0001). This was the only significant term in the model. The assumptions for constant variance and normality were checked using diagnostic plots generated by SAS. Each sweetpotato hill can be considered as independent from other hills. A residuals vs predicted values was plotted (see Appendix A, Figure S3) to check for non-constant variance and a quantile-quantile plot (see Appendix A, Figure S3) was inspected to see if the normality assumption was reasonable. The lsmeans for the ground speed and the interaction with the variety were plotted in Figure 2.43.

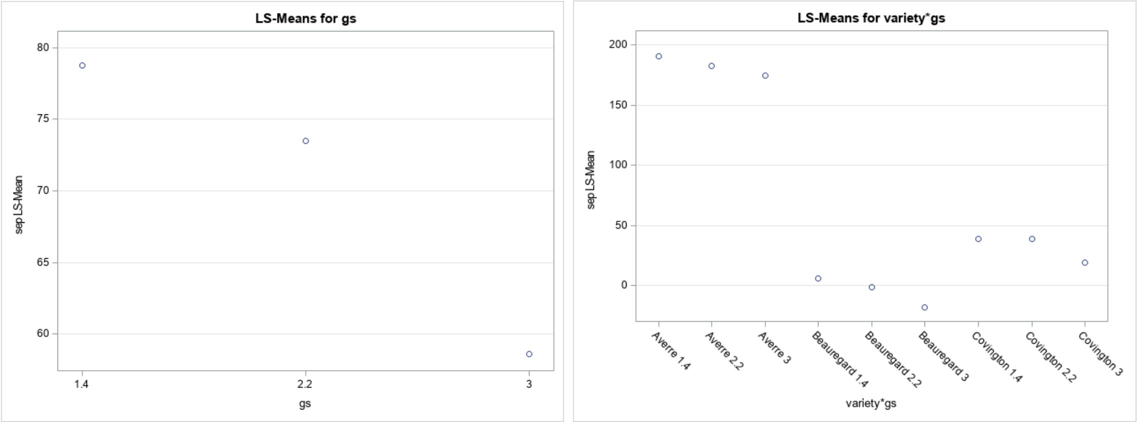

Figure 2.43: The lsmeans plot for the ground speed (left) and the interaction with variety (right)

The ground speed effect on the separation efficiency was negative and constant across the three varieties with a speed of 1.4 mph achieving higher separation efficiency compared to 2.2 mph and 3 mph. The interaction of ground speed and variety was not significant in the model (p-value = 0.75), suggesting that the effect of ground speed is constant across varieties, which can also be inspected in Figure 2.43. Tests for simple effects of ground speed for each variety are shown in Table 2.10.

Table 2.10: Tests for simple effects of ground speeds at each variety (Variety*Ground Speed effect sliced by Variety) for separation efficiency as response

Variety	DF	Sum of Squares	Mean Square	F Value	Pr > F
Averre	2	392.5098	196.2549	2.59	0.0947
Beauregard	2	1225.6462	612.8231	8.10	0.0019
Covington	2	924.0628	462.0314	6.11	0.0069

Similar analysis was done for the damage percentage as the response variable. The ANOVA (Table 2.11) for the model containing the effects of ground speed, variety, their interaction, soil moisture and soil temperature had an R-square value of 0.53. A test of equality of percentage roots damaged across all treatment combinations was rejected (p-value = 0.023).

Table 2.11: ANOVA of linear model for the percentage damaged as response

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	10	207.1599	20.7155	2.66	0.0230
Error	25	194.6670	7.7861		
Corrected Total	35	401.8261			

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Variety	2	163.1601	81.5801	10.48	0.0005
Ground Speed	2	23.8745	11.9371	1.53	0.2355
Soil Moisture	1	2.2274	2.2273	0.29	0.5975
Soil Temperature	1	3.6512	3.6513	0.47	0.4998
Variety*Ground Speed	4	14.2445	3.5612	0.46	0.7662

The observed variation of the percentage damaged across the three varieties was highly significant (p-value = 0.0005) in the model which meant that the average percentage roots damaged was affected by the variety. This was the only significant term in the model. The assumptions for constant variance and normality were checked using diagnostic plots generated by SAS. Each sweetpotato hill can be considered as independent from other hills. A residuals vs predicted values was plotted (see Appendix A, Figure S4) to check for non-constant variance and a quantile-quantile plot (see Appendix A, Figure S4) was inspected to see if the normality assumption was reasonable. The lsmeans for the ground speed and the interaction with the variety were plotted in Figure 2.44. The ground speed effect on the percentage roots damaged was positive for Beauregard and Covington varieties. The ground speed effect was not significant for all the varieties.

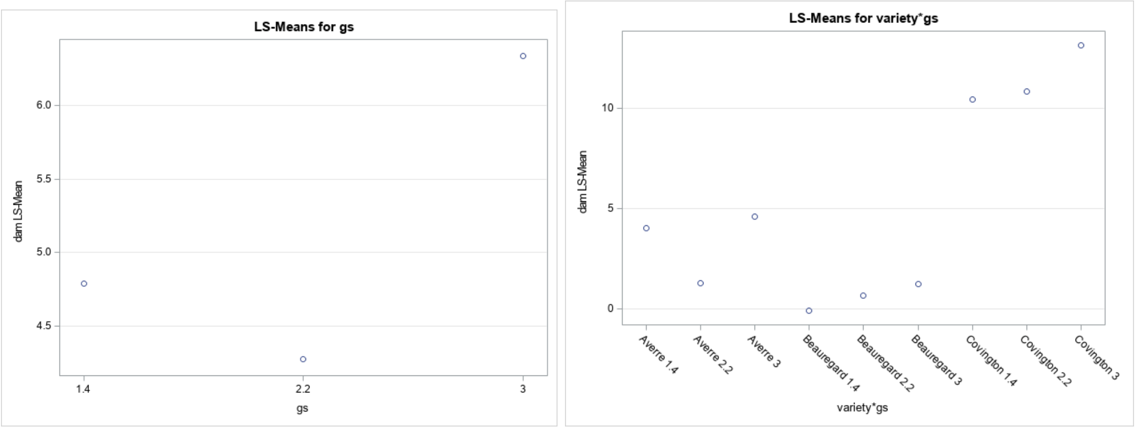

Figure 2.44: The lsmeans plot for the ground speed (left) and the interaction with variety (right)

From the observation during field tests and the analyses, it is best to operate the vine puller-chopper harvesting aid at 1.4 mph as it achieved higher separation efficiency compared to 2.2 mph and 3 mph for all the varieties. The percentage damaged roots was not significantly affected by the ground speeds and was dependent on the variety. It was observed during field tests that for the Covington variety, the roots protruded out of soil and were scraped by the machine rollers and damaged more than the other varieties. For the machine to work best for Covington variety and minimize the damage, more soil needs to be placed on top of the roots.

2.5. Summary and Conclusions

There was considerable progress in the development of the vine puller-chopper harvesting aid from the one-row prototype to the two-row unit in terms of consistency, continuity, performance and operation. The harvesting aid developed could operate for row lengths of above 2500 ft covering more than one acre without clogging or developing mechanical issues, which was considerably more than any other harvesting aid developed in the past. This was a huge improvement on the previous attempts reported in the literature to develop a machine for pre-harvest vine disposal. The separation efficiency, as a measure of performance for the harvesting aid, was on average approximately 70% for Beauregard, Covington, Bellevue and

Averre varieties. However, the Jewel variety had much lower separation efficiency values and can be deemed not suitable for the harvesting aid. Weed interference in the sweetpotato fields could lead to large yield losses (Seem et al. 2003; Meyers et al. 2010; Meyers and Shankle 2016). The harvesting aid was able to destroy pig weed of over 24 inches tall and 2 inches thick and also any other weeds growing in the field as well. The separation efficiency numbers obtained were consistent with those mentioned in literature by Hammerle (1970), Humphries and Abrams (1975) and Smith and Wright (1994) with a major difference being that the numbers obtained by the harvesting aid developed were over much greater row lengths. It was observed that the harvesting aid caused more damage to the Covington crop compared to any other variety it was tested on. One potential way to reduce damage to the Covington roots is to place extra soil cover while growing the Covington crop to protect the roots from the vine puller-chopper harvesting aid. To minimize damage caused by the gauge wheels and the pinch-rollers, adding an outer layer of rubber coating should be considered in future.

A separation efficiency of approximately 70%, achieved on average by the vine puller-chopper harvesting aid in several of its field tests, would be acceptable for the adoption by the growers due to the lack of commercially available alternatives to achieve vine-root separation, however, this depends on the partial equipment costs associated with the machine which is discussed in Chapter 4. The harvesting aid overcomes the drawbacks of similar prototypes developed by researchers to achieve vine-root separation whose continuous operation was sensitive to external factors and was limited to short rows (< 100 ft), although achieving comparable separation efficiency numbers. With an average separation efficiency of approximately 70%, the robust design of the vine puller-chopper harvesting aid makes it a great candidate for adoption by the sweetpotato growers for pre-harvest vine-root separation.

Although successful, the sweetpotato vine puller-chopper harvesting aid performance and efficiency can be improved. A challenge in using the harvesting aid is the difficulty encountered in its setup and adjustment to a new field with different field conditions, such as row spacing and soil depth. To make this better, an independent functioning modular row unit (Figure 2.45) which could easily be adjusted to new fields, should be explored in the future. The harvesting aid is also dependent on the tractor hydraulics. Ideally, the harvesting aid should have an independent hydraulic unit to minimize issues associated with using tractor hydraulics. In fact, with the uncertainty of the tractor hydraulic flowrates, it would probably be ideal to use a PTO driven hydraulic unit for the vine puller-chopper harvesting aid in future designs. Design improvements to the harvesting aid to operate at higher ground speeds (> 3mph) without drastically affecting its performance should be considered in the future. In being even more ambitious, a vine puller-chopper which is a hybrid between a disc plow and a chain digger in terms of functionality in order to incorporate the vine-root separation and the inversion of the soil bed into the same unit to make it a one-pass system for harvesting should be considered in the future.

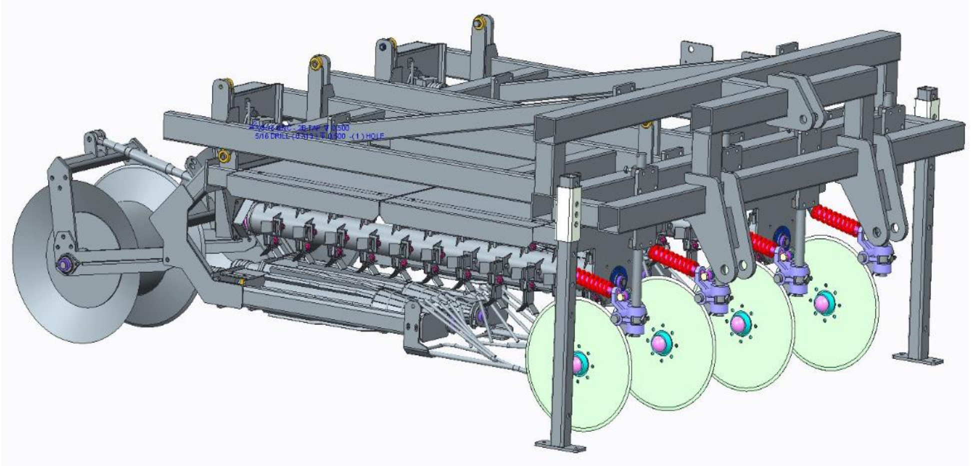

Figure 2.45: Modular two-row vine puller-chopper unit designed for possible future testing

The vine puller-chopper harvesting aid was developed to improve the capabilities of mechanical harvesting techniques and its field testing demonstrated that it can be successful. An alternate version of a harvesting aid for sweetpotatoes which was designed in SolidWorks but not developed, was a vine puller-chopper design using a belt system (Figure 2.46) to grasp and pull the vines. This design can be explored in the future as an alternative to the harvesting aid.

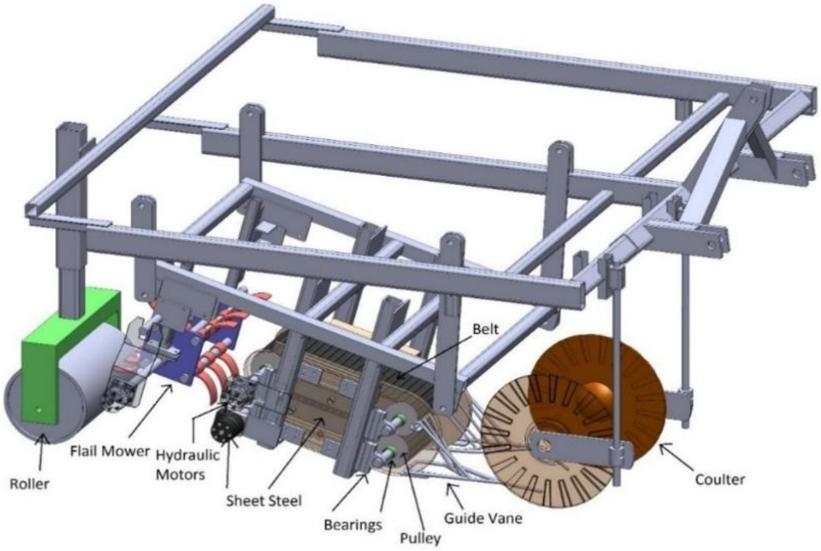

Figure 2.46: Belt design of a harvesting aid to achieve vine-root separation

2.6. References

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CHAPTER 3: Field Evaluation of the Vine Puller-Chopper Harvesting Aid: Skin Strength Enhancement of the Roots

3.1. Abstract

Previous research has resulted in a vine puller-chopper harvesting aid capable of achieving nearly complete vine-root separation. Many researchers have hypothesized that mechanical and chemical treatments such as vine removal, undercutting or spraying ethephon are beneficial for toughening the sweetpotato root skin and reducing the damage to the roots during harvesting and post-harvest handling. This chapter investigates the effect of vine-root separation using the harvesting aid developed as a pre-harvest operation on the skin strength of the sweetpotato roots over time. Three fields each of Beauregard and Covington varieties were evaluated. A modified version of the Halderson Periderm Shear Tester and Torquometer was used for measuring the skin torsion and normal load required to tear the sweetpotato root skin surface for roots with their vines removed by the harvesting aid as well as for the roots with their vines intact as a measure of skin strength over a 16-day period. There was an overall increase in the observed skin torsion and normal load values for both the varieties when the harvesting aid was used compared to when it was not used. The maximum average skin torsion was 1.99 lb-in for the Beauregard variety and 1.47 lb-in for the Covington variety. The corresponding maximum average normal load values were 20.58 lb and 17.02 lb for Beauregard and Covington, respectively. Values were much lower when the vine puller-chopper harvesting aid was not used. The quantification of skin strength over time can provide very useful information for growers and the equipment manufacturers to reduce damage to the roots during harvesting and post-harvest handling.

3.2. Introduction

Sweetpotatoes are typically harvested approximately 90 to 120 days after planting, although this depends on the cultivar, plant spacing and weather conditions. In North Carolina, harvesting typically involves mechanical aids such as a disc plow or a chain digger inverting a depth of the soil profile and placing the roots on top of the soil. A farm crew then picks up the roots and places them into bins. During harvesting and post-harvest handling of sweetpotatoes, the outer layer of periderm has a significant chance of being separated from the underlying root tissue (Villavicencio et al., 2004). Sweetpotato roots have delicate, easily damageable skin and are torn with the slightest of tangential force (shear) applied at harvest (Goodman and Hamann, 1971). Direct impact perpendicular (normal) to the surface of the root is much less damaging.

Any damage caused to the root skin can lead to moisture loss, microbial attacks and poor overall cosmetic quality of the sweetpotato. Further, the wounded areas due to the skin damage can easily be mistaken for fusarium rot according to Blankenship and Boyette (2002) and Clark et al. (2013). The skin damage caused at harvesting can have a detrimental effect on the storage longevity. Edmunds et al. (2008) showed that up to 25% of sweetpotatoes were lost due to moisture loss and decay during storage because of skin damage during harvesting. In a study conducted by Boyette (2009), the ratio of salable sweetpotato weight out of storage after about 10 months was approximately 0.6 with unregulated storage facilities.

A standard practice for growers to reduce damage and abrasions to the roots at the time of harvest is to de-vine, which involves partial or complete removal of vines prior to harvesting. This is achieved either by mowing the vine material close to the surface or by using harvesting aids such as a vine puller-chopper to separate the vines completely from the roots. This method of de-vining is typically done a few days before harvest to slow down the root growth and to initiate the skin set process (Hayes et al., 2014). According to experiments conducted by Dukuh (2011), defoliation of the sweetpotatoes prior to harvest significantly reduced the damage and rot during harvesting and post-harvest handling. Defoliation approximately 10 days prior to harvesting reduced skinning damage by 62% according to La Bonte and Wright (1993).

It has been hypothesized that vine removal can have the benefit of increasing the skin toughness and enhancing the sweetpotato root-skin adhesion (Hayes et al., 2014). Skin adhesion or skinning resistance shows the capacity of the periderm to resist skin fracture. The periderm acts as a barrier to the roots from the outside environmental conditions as well as decay organisms. Root skin adhesion depends on the sweetpotato variety and is affected by the environmental conditions and growing practices (Rees et al., 2003; Villavicencio et al., 2007). Toughening the skin and increasing the skin adhesion is likely to reduce damage during harvesting and post-harvest handling.

Mechanical pre-harvest treatments such as de-vining as much as 14 days prior to harvest were deemed to be beneficial to reduce sweetpotato skinning compared to no treatment (Schultheis et al., 2000). De-vining about a week prior to harvesting controls root growth and toughens the root skin by initiating skin setting (Dukuh, 2011; Arancibia et al., 2013; Wang et al., 2013; Hayes et al., 2014). Hayes et al. (2014) hypothesized that ‘undercutting’ of sweetpotato storage root initiates quicker setting of skin as compared to the traditional method of de-vining by cutting off the nutrient supply from the soil beneath the roots and sending the sweetpotato roots in to a state of sudden ‘shock’. Skinning injury is not only caused by the equipment involved in harvesting or post-harvest handling but is also caused by the abrasions on the roots due to their interaction with the soil clods and vines (Figure 3.1). Mechanical harvesting of sweetpotatoes involving a conveyor digger causes skinning due to rapid motion of soil over the roots (Lebot, 2009). It has been suggested that the use of soil additives such as biochar could change the physical properties of the soil which could help reduce the skinning caused by them during harvesting (Hayes et al., 2014).

Figure 3.1: Soil clods and vines deposited in the bins during harvesting along with the sweetpotato roots

Studies indicate that the post-harvest losses in weight and moisture along with microbial rots are a direct consequence of the bruising and damage caused to the roots during the harvesting process. Arancibia et al. (2013) reported that application of pre-harvest treatments such as ethephon helped set the skin to reduce skinning damage during harvest (LaBonte and Wright, 1993; Schultheis 2000); however up to seven days before harvest is likely to increase tip rot incidence for the Beauregard variety. Tomlins et al. (2002) observed the effects of pre-harvest canopy pruning up to 18 days before harvest on skinning injury during harvest and shelf life after harvesting and suggested that the canopy be removed up to 14 days before harvest to minimize skinning damage and improve shelf life. They indicated that this practice is a form of curing and that this reduced skinning injury during harvesting and post-harvest handling along with any rot incidences. Wang et al. (2013) determined that the force needed to skin the roots increased for de-vined roots if conducted at least three days prior to harvest with reduced skinning incidences.

The rupture force and amount of deformation values reported by Wright and Splinter (1968) can serve as a basis when designing components for harvesting or post-harvest handling operations. Results published by Fluck et al. (1968) corroborated the research done by Wright and Splinter in terms of the force required for sweetpotato root skinning.

Curing of sweetpotatoes involves the roots being placed in a warm room or facility at a temperature of approximately 85°F with enough ventilation and a relative humidity of approximately 90% for 4 to 7 days immediately after harvesting (Edmunds et al., 2008). The time required for proper curing depends on the temperature of the roots at the time of harvest relative to the 85°F temperature (Edmunds et al., 2008). This process helps dry the roots and promotes O_2 and CO_2 exchange. Further, the curing process promotes wound healing and prevents decay or disease from spreading. Curing is also known to be useful to set the sweetpotato skin preventing damage during subsequent postharvest handling (Blankenship and Boyette, 2002). Curing reduces postharvest losses as the curing process will cover the dead cells in the areas of the wounds, a process known as suberization (Lewthwaite and Triggs, 2012). Additionally, curing heals the cuts and damage to the roots improving their visual appeal to the consumer as well as enhancing the taste of the cooked roots. Excessive curing of sweetpotatoes, however, can cause sprouting of the roots during storage which results in rapid weight loss and subsequently reduces the shelf life. Optimum temperature and humidity are required during curing without which there are chances that there is increased weight loss and insufficient healing of the wounds resulting in decreased shelf life of the roots (Edmunds et al., 2008).

It is important to understand the mechanical properties of sweetpotato roots under various types of loading that they may be subjected to during harvesting or post-harvest handling. Sweetpotatoes that are sent to the market compete directly with other produce like white potatoes with a major emphasis given to appearance, in addition to better nutritional qualities. Therefore, even the slightest damage caused during harvest can significantly affect the market space for sweetpotatoes. Hammerle (1970) established that a maximum dropping height of six inches onto a steel surface can occur without causing any bruises to the sweetpotato roots. Wright and Splinter (1968) characterized the mechanical failure of storage root tissue by rupture force, deformation rate and energy required under slow and impact loading for different cultivars.

Some of the harvesting and post-harvest handling systems for the sweetpotato roots in the tropics resulted in more than 50% of the roots with severe skinning damage (Ray and Ravi, 2005). It is therefore important to reduce the wounds and damage caused to the root skin. One way of achieving this is to toughen the skin or increase the skin strength prior to harvest. Sweetpotato skin strength can be considered as the force required to rupture the skin by shear or torsion under a certain normal load (Wright and Splinter, 1968). Skin strength values were reported by Hayes et al. (2014) at intervals of 3 and 6 days after undercutting of Beauregard and Evangeline sweetpotato cultivars. The shear and normal forces required to rupture the periderm of the roots give a measure of the skin strength of the sweetpotatoes. According to Villavicencio et al. (2004) the skin strength can improve during storage with the extent of improvement not related to the skin strength during harvest which is influenced by the growing conditions of the cultivar. The improvement of skin strength due to preharvest conditions is an important consideration because many researchers including Smith and Wright (1994) have hypothesized skin strength or toughness of the sweetpotato roots is increased because of pre-harvest treatments such as de-vining, undercutting and chemical applications, however, none of them have definitively quantified it.

Thus, earlier research suggests that further investigation should be done on reducing the skin damage and separation at the time of harvest. Development of a sweetpotato vine puller-chopper harvesting aid to separate the main stem from the individual roots below the soil has been an important step towards reducing sweetpotato skinning. Quantifying the effect of the vine-root separation by the harvesting aid on the skin strength of the sweetpotato roots prior to harvest is a key objective of this study. The hypothesis is that the vine-root separation initiates the skin set process by cutting the nutrient supply and water intake to the sweetpotatoes and as a reaction to the change, the root skin would toughen. This study involving the quantification of skin strength due to vine-root separation by the vine puller-chopper machine should provide the sweetpotato growers with information on skin toughness during harvesting. Additionally, this study should also benefit the sweetpotato equipment manufacturers to design the appropriate harvesting and post-harvest machinery to minimize skin damage. At a larger scale, this study should enhance technology development in the sweetpotato industry and help in mechanizing the harvesting process.

3.3. Methodology

Three commercial sweetpotato fields each of Covington and Beauregard varieties near Faison, Mount Olive and Newton Grove, NC, were used in this study. Data from the fields were collected over a two-year period during the 2016 and 2017 harvesting seasons, two Beauregard fields and one Covington field in the 2016 season and two Covington fields and one Beauregard field in the 2017 season. The fields were all managed by Burch Farms and were grown under standard cultural practices (Schultheis et al., 1999; Meyers et al., 2010). Eight randomly selected rows from each field were ‘snatched’ to separate the vines and main stem from the roots by operating the vine puller-chopper harvesting aid. At similar times after the harvesting aid was used, three hills were randomly selected from the snatched rows operated by the harvesting aid and from rows in which the harvesting aid was not used to serve as a control measurement and were dug for skin strength measurement. The three roots from each selected hill in which vines were separated from roots were sampled for measuring the skin strength at 0, 4, 8, 12, and 16 days after operating the harvesting aid. Skin strength was measured in the field using a modified version of the Halderson Periderm Shear Tester and Torquometer (Halderson and Henning, 1993; Lulai and Orr, 1993; Hayes et al., 2014) as shown in Figure 3.2.

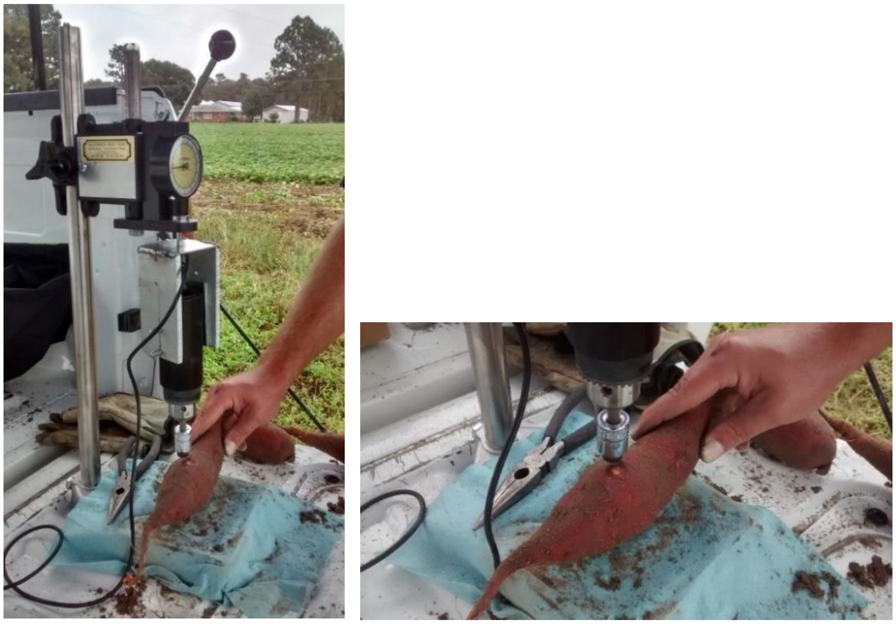


Figure 3.2: Modified version of the Halderson Periderm Shear Tester and Torquometer to measure the skin strength of the sweetpotato roots

The Halderson Periderm Shear Tester and Torquometer (Figure 3.3) as described by Hayes et al. (2014) consists of a rubber tip on the end of a spring shaft which is connected to a digital torquometer (TQ-8800, Lutron Electronic Enterprise, Taipei, Taiwan). The user pushes the rubber tip against the root skin using the spring shaft to apply the desired normal (compression) force and the tip is simultaneously rotated. The degree of which the rotation of the rubber tip with sufficient normal force shears the periderm away from the underlying cells is directly related to the toughness of the skin and its adhesion to underlying root cell layer. The digital torquometer connected can be set to read out the maximum skin torsion (kg-cm) required to perform this action and shear the skin. The skin torsion values in kg-cm were later converted to lb-in units for data consistency. The instrument alone has no means of measuring the normal load applied to achieve the skin shear.

Figure 3.3: Digital torquometer and Halderson Shear Tester with spring loaded shaft for applying constant normal force (Hayes et al., 2014)

The torsional force alone as recorded by the torquometer is not a sufficient indicator of skin strength. The skin strength measurement is incomplete without measuring the corresponding normal force along with the torsional force required to shear the skin. The smallest normal force that shears the root skin along with the corresponding torsional force that brings about the skin tear are considered to be a complete measure of skin strength. To obtain the normal force measurements along with the torsional force required to shear the skin, the Halderson Periderm Shear Tester and Torquometer was modified by removing the spring-loaded shaft and integrating the torquometer with a fruit pressure tester (FT 327 Penetrometer, QA Supplies LLC, Norfolk, VA), with a maximum compression capacity of 28 lb (Figure 3.4). This combined version of the two instruments as shown in Figure 3.2 was used to obtain the skin strength measurements in terms of the maximum skin torsion (kg-cm), later converted to lb-in, required to shear the root skin along with the corresponding normal load (lb) associated with it.

A half inch rubber stopper in a socket was used as the shearing interface. Care was taken to avoid the rubber stopper from slipping in the socket before the sweetpotato root skin sheared by applying glue to the inside walls of the socket. The torsional motion of an object encountering the root skin will shear the periderm away from the underlying surface cells after the maximum shear limit is reached. An incremental normal load was applied with the fruit pressure tester on each selected root as an iterative process to determine the minimum normal load at which the root skin sheared caused by the rotation of the rubber tip against the root surface. The corresponding skin torsion output that caused the shear was recorded from the digital torquometer output along with the corresponding normal load.

Figure 3.4: Modified version of the Halderson Periderm Shear Tester and Torquometer constructed at the BAE Research Shop, NCSU and integrated with the fruit pressure tester

A minimum of 3 measurements of the skin torsion and corresponding normal load were collected from the equatorial region (Figure 3.2) of each selected root as the root skin sheared. The skin torsion and the normal load were averaged over each root and each hill. The resulting skin torsion and normal load values were averaged over the three randomly selected hills from each field for each day of measurement from 0, 4, 8, 12 and 16 days after selected rows were operated by the vine puller-chopper harvesting aid. The same method was used to compute the average skin torsion and normal load for the control roots for each field with their vines intact. The torque to shear and normal forces required to rupture the periderm of the roots provided a measure of the skin strength of the sweetpotatoes. The average skin torsion and the corresponding normal load were computed for both the snatched and unsnatched (control) roots from each field 0, 4, 8, 12, and 16 days after operating the harvesting aid.

The soil moisture and the soil temperature were recorded for each field using the HOBO micro station data logger (H21-002, Onset Computer Corporation, Bourne, MA) with the soil moisture smart sensor (S-SMD-M005, Onset Computer Corporation, Bourne, MA) at the time the skin strength data for the roots were collected. The soil moisture and soil temperature were measured at a constant depth of 6 inches below the soil cover of the planted rows from which the roots were sampled 0, 4, 8, 12, and 16 days after operating the harvesting aid at two random locations in each field. The recorded soil moisture and soil temperature were considered to be a representation of the entire field for each day the skin strength data was collected. The soil moisture and soil temperature were recorded also, since they are variables that may influence the skin strength measurements (Gajanayake et al., 2014; Hayes et al., 2014). The average skin torsion (kg-cm), corresponding average normal load (lb), soil temperature (°F) and soil moisture ($in^3\ in^{-3}$) data obtained for each field of Beauregard and Covington for both snatched and control roots at intervals of 0, 4, 8, 12, and 16 days after being operated by the harvesting aid (DAT) were tabulated (Table 3.1) with the skin torsion values converted to lb-in for consistency.

Table 3.1: Average skin torsion, normal load, soil moisture, and soil temperature values measured for each field of Beauregard and Covington at 0, 4, 8, 12, and 16 days (DAT) after being operated by the vine puller-chopper harvesting aid.

				Snatched		Control (Unsnatched)	
Variety	**DAT**	**Soil Moisture ($in^3\ in^{-3}$)**	**Soil Temp. (°F)**	**Avg. Skin Torsion (lb-in)**	**Avg. Normal Load (lb)**	**Avg. Skin Torsion (lb-in)**	**Avg. Normal Load (lb)**
Beauregard	0	0.109	60.700	0.37	4	0.37	4
Beauregard	4	0.300	59.300	0.72	7	0.43	5.7
Beauregard	8	0.172	72.800	1.26	13.87	0.56	4.83
Beauregard	12	0.115	74.100	1.86	17.3	0.55	5.38
Beauregard	16	0.266	57.300	2.15	24.2	0.58	4.55
Beauregard	0	0.089	59.200	0.39	4	0.40	4.2
Beauregard	4	0.285	62.100	0.39	6.5	0.52	5.3
Beauregard	8	0.148	73.900	1.42	15	0.45	4.3
Beauregard	12	0.095	75.800	2.15	20	0.75	6.3
Beauregard	16	0.245	62.500	1.82	20	0.61	4.2
Beauregard	0	0.165	74.500	0.52	5	0.43	5
Beauregard	4	0.158	76.000	0.61	5	0.61	5.3
Beauregard	8	0.162	65.500	0.87	10	1.04	8.5
Beauregard	12	0.203	71.800	1.48	12.8	0.61	6
Beauregard	16	0.167	76.900	2.00	17.55	1.04	8.5
Covington	0	0.033	58.700	0.45	4.5	0.43	4.5
Covington	4	0.180	58.000	0.83	7.6	0.42	4.5
Covington	8	0.089	76.900	1.50	18.08	0.58	5.2
Covington	12	0.042	71.800	1.49	18.06	0.61	4.83
Covington	16	0.175	56.500	1.72	21.5	0.55	4.5
Covington	0	0.061	63.500	0.43	4.82	0.43	4.82
Covington	4	0.049	69.000	0.60	5.95	0.39	4.82
Covington	8	0.073	58.700	0.61	6.64	0.61	6
Covington	12	0.068	64.400	0.87	13.91	0.61	4.82
Covington	16	0.080	61.800	1.11	11.75	0.87	6.5
Covington	0	0.107	55.300	0.32	4.82	0.30	4.82
Covington	4	0.099	62.700	0.54	7	0.87	9
Covington	8	0.126	70.800	0.62	9	0.39	5.3
Covington	12	0.095	66.000	1.43	15	0.61	4.82
Covington	16	0.095	60.000	1.56	17.8	1.13	13.5

The skin strength data from Table 3.1 were analyzed using the MIXED procedure in SAS software (SAS Institute, 2017). Each of the six fields was considered as a plot with the assigned variety of Beauregard or Covington. A linear mixed effects model was used to investigate factorial effects of interest. Average skin torsion (lb-in) and the average normal load (lb) required to shear the sweetpotato root skin were considered as response variables. Variety (Beauregard and Covington), treatment (snatched and control (unsnatched)) and DAT (0, 4, 8, 12 and 16 days after being operated by the harvesting aid) were the considered factors. The soil temperature (°F) and soil moisture ($in^3 \, in^{-3}$) were also considered as variables that may have an effect on the response. In particular, fixed factorial effects were included for treatment, DAT, variety and all interactions among them. As the varieties were assigned to entire plots with varying levels of treatment and DAT on each plot, in a repeated measures design, random effects were included for plot nested in variety.

3.4. Results and Discussion

Average skin torsion and average normal load were plotted for each field in relation to the number of days after operating the harvesting aid for both the snatched and the control (unsnatched) roots. The average skin torsion and normal load for the first Beauregard field study in 2016 is shown in Figure 3.5. Both the skin torsion as well as the normal load required to shear the root skin increased with the number of days after operating the harvesting aid. The average skin torsion increased from 0.37 lb-in to 2.15 lb-in over the 16-day period for the snatched roots from which the vines were completely separated. The average skin torsion fluctuated between 0.37 lb-in and 0.58 lb-in in the same 16-day period for the control roots with their vines intact. The corresponding average normal load ranged from 4 lb to 24 lb over the 16-day period for the snatched roots while it fluctuated between 4 lb and 5.38 lb for the roots with their vines intact.

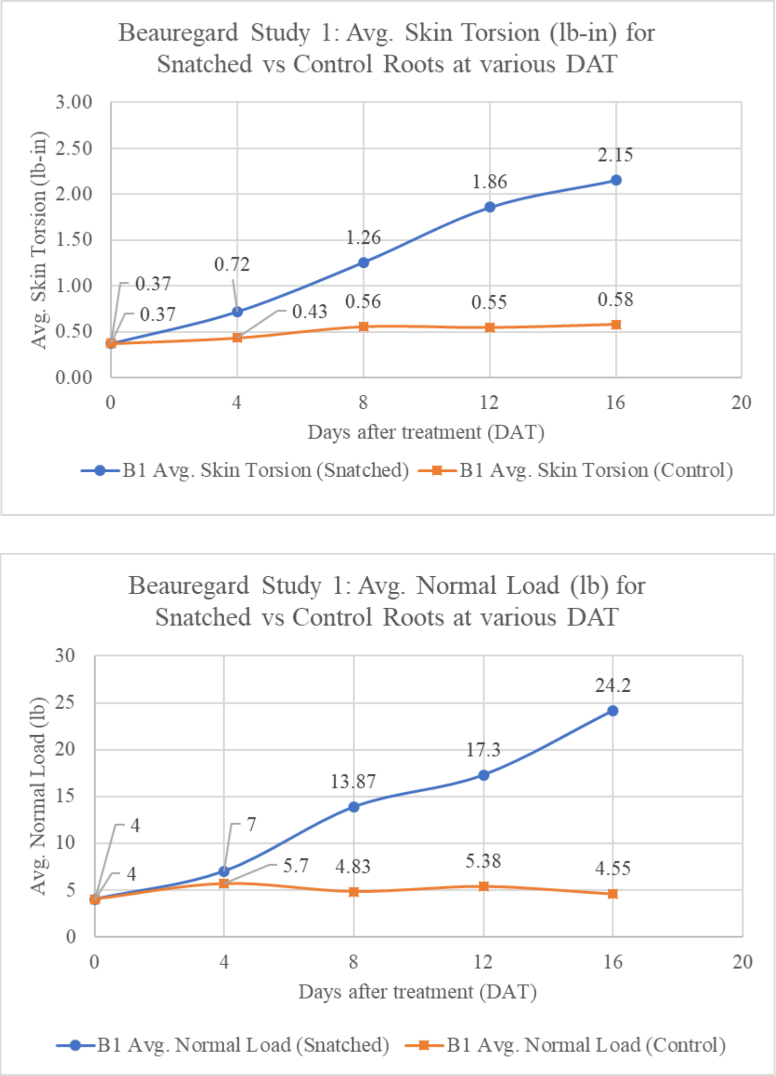


Figure 3.5: Average skin torsion (above) and normal load (below) plots for the first Beauregard field in 2016 for the snatched and control roots with respect to the number of days after using the harvesting aid

The average skin torsion and normal load for the second Beauregard field study in 2016 is shown in Figure 3.6. There was an overall increase in the skin torsion values for both the snatched and control roots in the field through 12 DAT, then skin torsion values leveled off or decreased slightly. The reduction in torsion values may have been due to the increase in soil moisture between the days 12 and 16 making the skin softer and easier to shear. The increase in the skin torsion for the snatched roots was much higher compared to the increase in the skin torsion for the control roots. Average skin torsion increased from 0.39 lb-in to a maximum of

2.15 lb-in for the snatched roots. Average skin torsion for the control roots varied from 0.4 lb-in on day 0 to a maximum of 0.75 lb-in on day 12 and then decreased to 0.61 lb-in on day 16. There was a significant change in the soil moisture and temperature between day 12 and 16 for the second Beauregard field study and may have been the cause for the drop in the skin torsion values for the roots as already mentioned. The corresponding normal load values ranged from 4 lb to 20 lb for the snatched roots over the 16-day period while it fluctuated between 4.2 lb and 6.3 lb for the roots with vines intact.

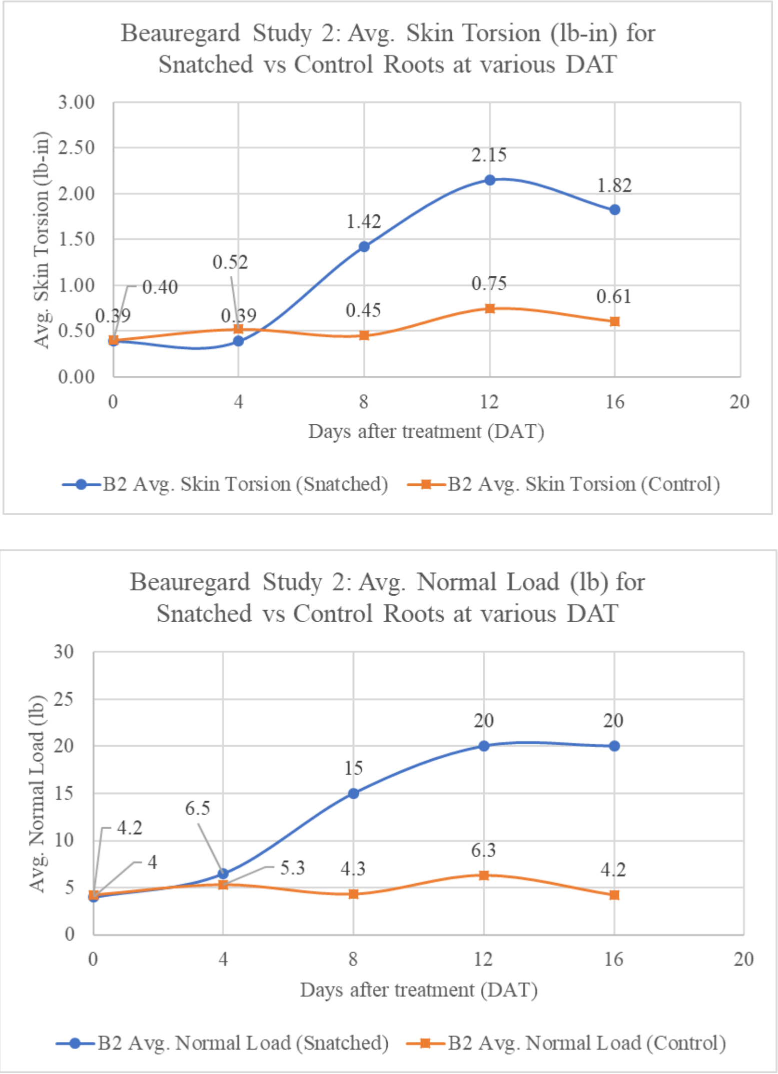


Figure 3.6: Average skin torsion (above) and normal load (below) plots for the second Beauregard field in 2016 for the snatched and control roots with respect to the number of days after using the harvesting aid

The average skin torsion and normal load for the third Beauregard field study in 2017 is shown in Figure 3.7. Both the average skin torsion and the normal load values increased over the 16-day period for the snatched roots with the skin torsion ranging from 0.52 lb-in to 2 lb-in and the normal load ranging from 5 lb to 17.55 lb. The corresponding values of the skin torsion and normal load for the roots with their vines intact fluctuated between 0.43 lb-in and 1.04 lb-in for the skin torsion and 5 lb to 8.5 lb for the normal load respectively. There was an overall increase observed in the skin torsion and normal load values for the control roots over the 16-day period

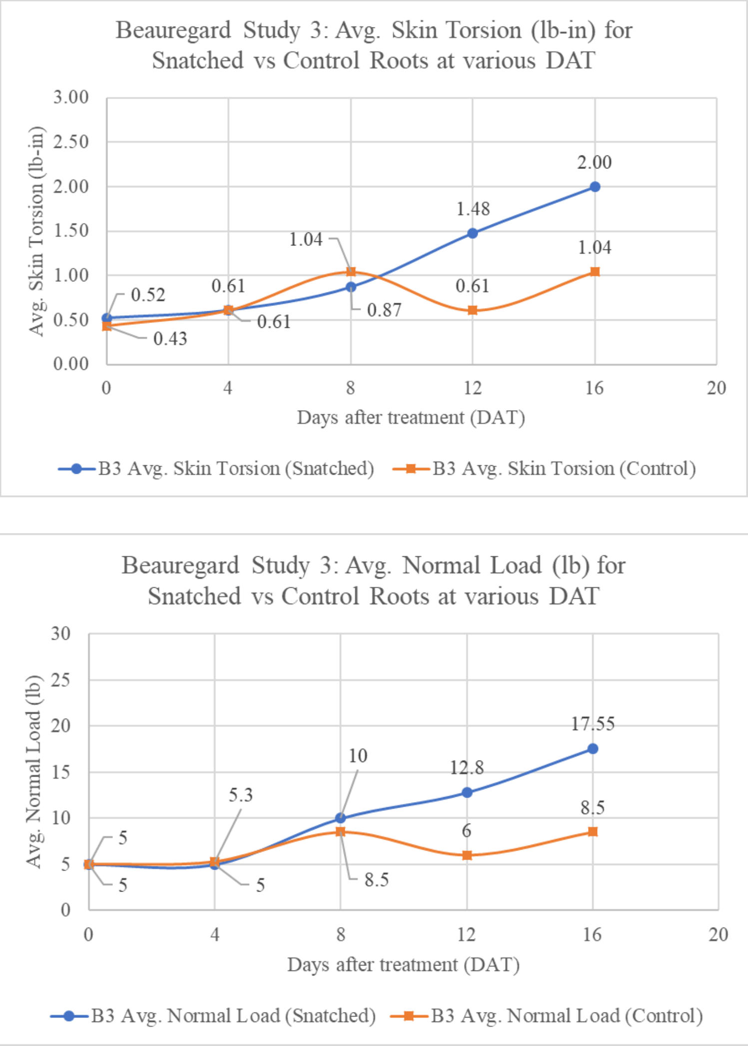


Figure 3.7: Average skin torsion (above) and normal load (below) plots for the third Beauregard field in 2017 for the snatched and control roots with respect to the number of days after using the harvesting aid

with the skin torsion values on day 8 slightly more than the corresponding values for the snatched roots with the normal load almost being the same. The average skin torsion values of the snatched roots being less than the control roots on day 8 for this Beauregard field study was an anomaly compared to the other field studies, although the measured skin torsion values of the snatched roots were consistent with the other field studies.

The average skin torsion and normal load for the first Covington field study in 2016 is shown in Figure 3.8. Both the average skin torsion and the normal load increased over time for

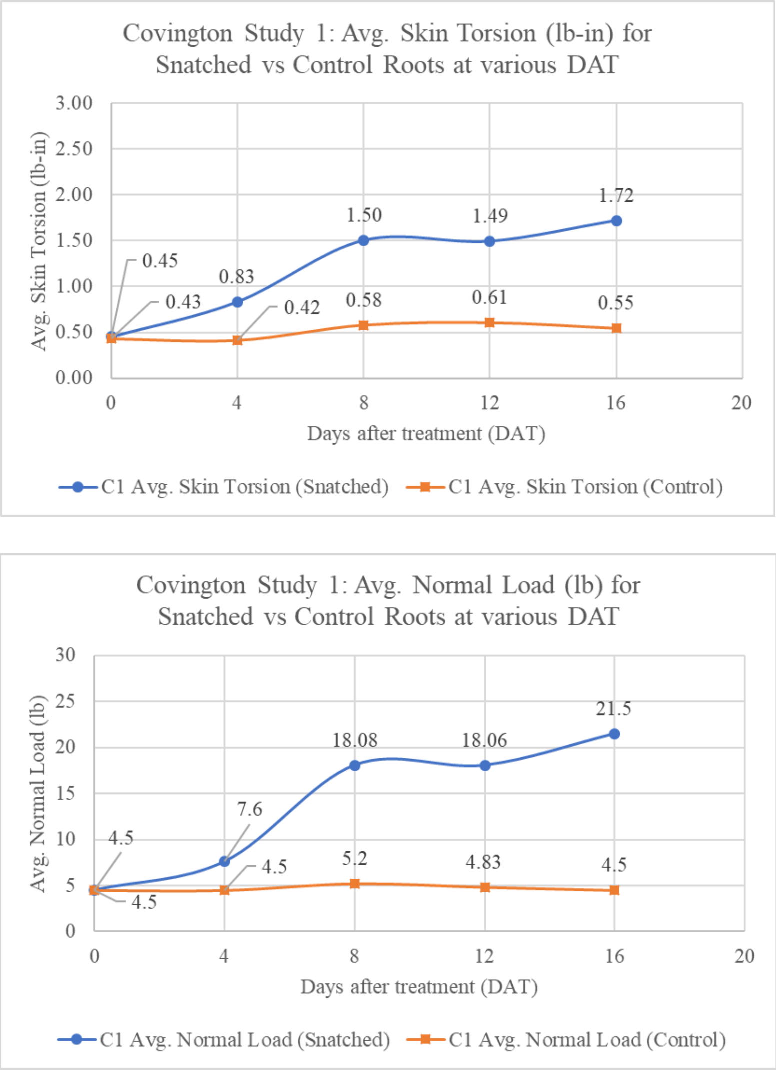


Figure 3.8: Average skin torsion (above) and normal load (below) plots for the first Covington field in 2016 for the snatched and control roots with respect to the number of days after using the harvesting aid

the snatched roots while these values were more constant for the roots where vines were left intact. Average skin torsion varied from 0.45 lb-in to 1.72 lb-in for the snatched roots and from 0.43 lb-in to 0.61 lb-in for the control roots. Average normal load ranged from 4.5 lb to 21.5 lb for the snatched roots and from 4.5 lb to 5.2 lb for the roots with their vines intact over the 16-day period.

The average torsion and normal load for the second Covington field study in 2017 is shown in Figure 3.9. There was little difference in the average skin torsion values for the snatched roots compared to the roots with the control treatment where vines were intact over the 16-day period. Skin torsion ranged from 0.44 lb-in to 1.11 lb-in for the snatched roots and from 0.43 lb-in to 0.87 lb-in for the control roots. The average normal load for the snatched roots was comparable to the corresponding values for the roots with their vines intact over the 8-day period after which there was a considerable increase in the average normal load for the snatched roots. The response of the snatched roots to the treatment of separating the main stem and vines form the roots in terms of having an increased skin strength seemed to be a little slow for this field study compared to the other field studies. A combination of the soil moisture and soil temperature values may have been a possible reason for this slow response. Normal load for the snatched roots was 13.91 lb on day 12 compared with 4.82 lb for the control roots. There was a general increase in the skin torsion and normal load values observed for both the snatched roots and the roots with their vines intact over the time of study for this field with a slightly higher increase in the values for the snatched roots compared to the control roots, especially at 12 or 16 DAT.

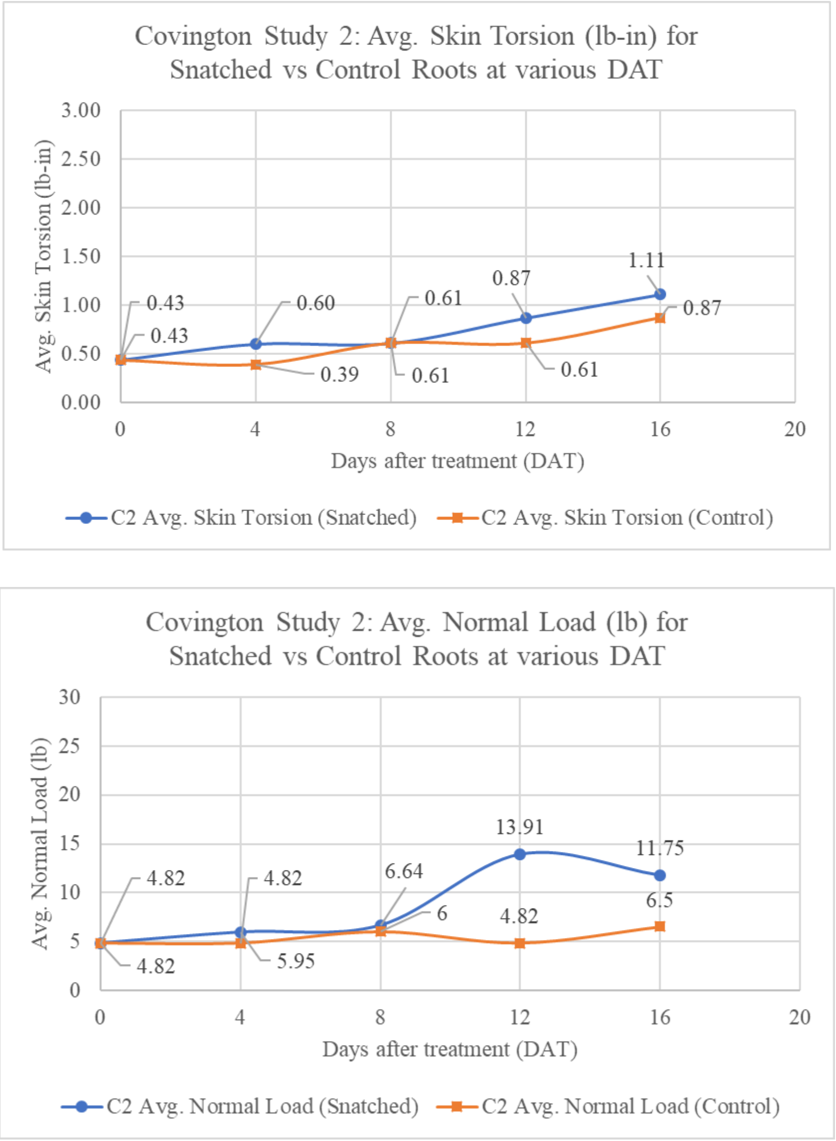
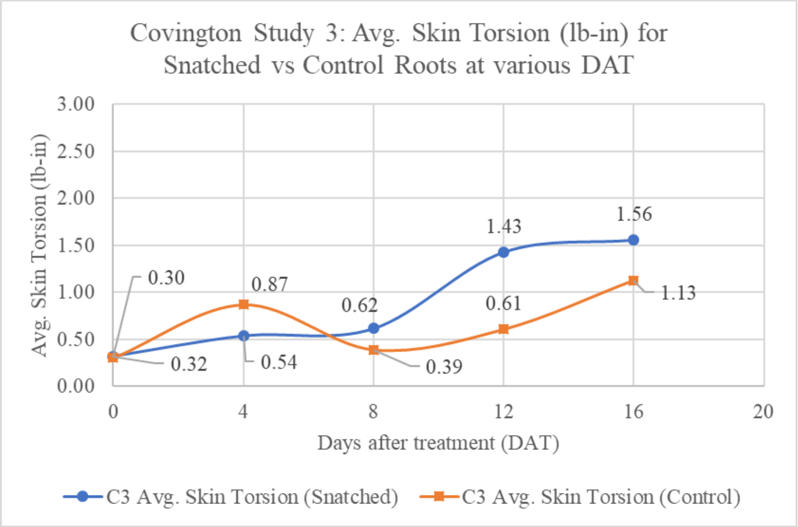


Figure 3.9: Average skin torsion (above) and normal load (below) plots for the second Covington field in 2017 for the snatched and control roots with respect to the number of days after using the harvesting aid

The average torsion and normal load for the third Covington field study in 2017 is shown in Figure 3.10. There was an overall increase in the skin torsion and normal load values for both the snatched roots as well as the roots with their vines intact over the 16-day period. The increase in the skin strength measures were, however, much higher for the snatched roots compared to the control roots. Average skin torsion ranged from 0.32 lb-in to 1.56 lb-in for the snatched roots and the corresponding average normal load varied from 4.82 lb to 17.8 lb. Skin torsion ranged from

0.3 lb-in to 1.13 lb-in for the control roots over the 16-day period and the corresponding normal load ranged from 4.82 lb to 13.5 lb.



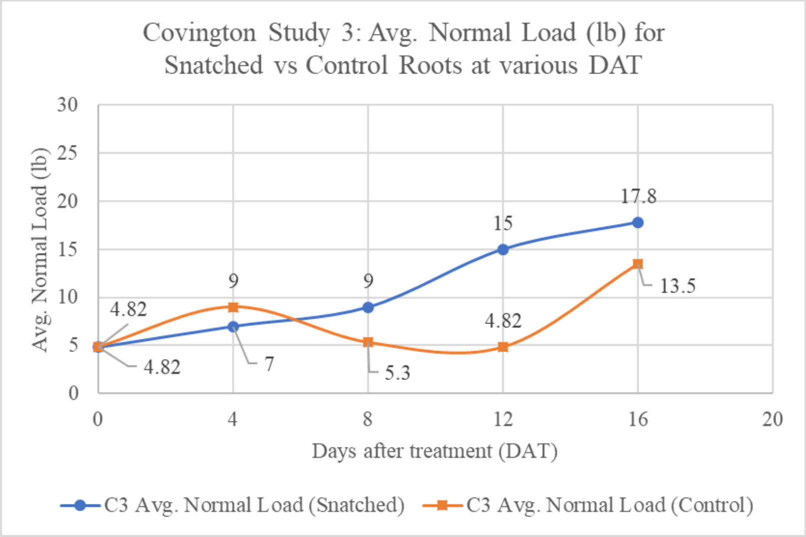


Figure 3.10: Average skin torsion (above) and normal load (below) plots for the third Covington field in 2017 for the snatched and control roots with respect to the number of days after using the harvesting aid

The average skin torsion and normal load for the three Beauregard field studies were computed and plotted in Figure 3.11. The average skin torsion values ranged from 0.43 lb-in to 1.99 lb-in for the snatched roots and from 0.4 lb-in to 0.74 lb-in for the control roots with their vines intact over the 16-day period. The corresponding average normal load varied from 4.4 lb to 20.58 lb for the snatched roots and from 4.33 lb to 5.89 lb for the control roots.

Similarly, the average skin torsion and normal load for the three Covington fields were computed and plotted in Figure 3.12. The average skin torsion values ranged from 0.4 lb-in to 1.47 lb-in for the snatched roots and 0.39 lb-in to 0.85 lb-in for the roots with their vines intact over the 16-day period. The corresponding average normal load varied from 4.71 lb to 17.02 lb

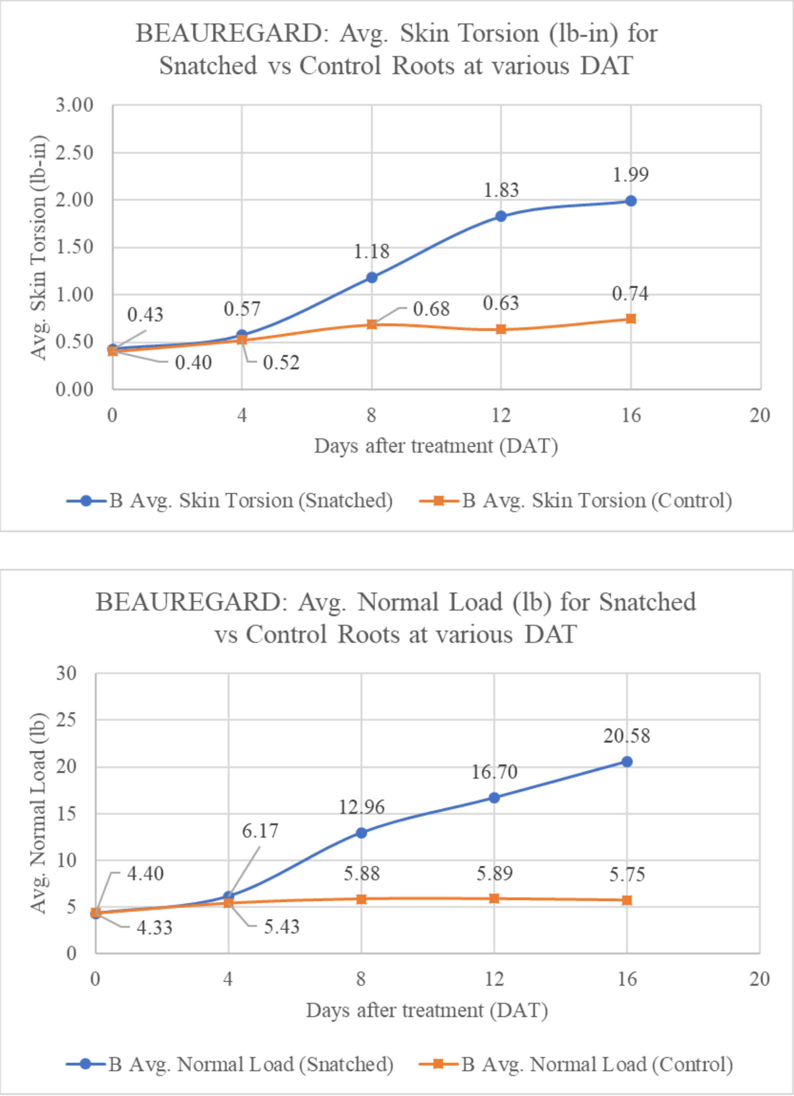


Figure 3.11: Average skin torsion (above) and normal load (below) plots for the three Beauregard fields for the snatched and control roots with respect to the number of days after using the harvesting aid

for the snatched roots and from 4.71 lb to 8.17 lb for the control roots. The Beauregard and the Covington varieties showed similar trends in relation to the increase in skin torsion and normal load values over the 16-day period for the snatched roots compared to the control roots. However, the increase in the skin torsion and normal load as a measure of the skin strength of the snatched sweetpotato roots was greater for Beauregard compared to Covington. The maximum average normal load for the snatched roots of the Beauregard variety was 20.58 lb compared to

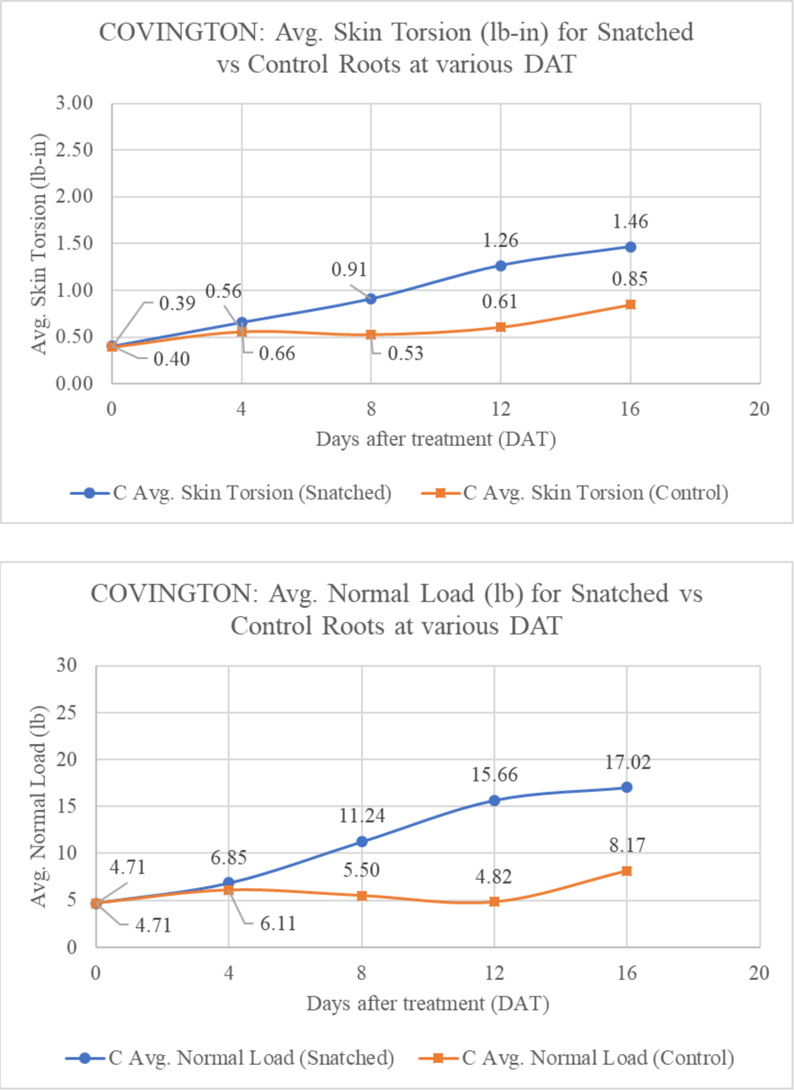
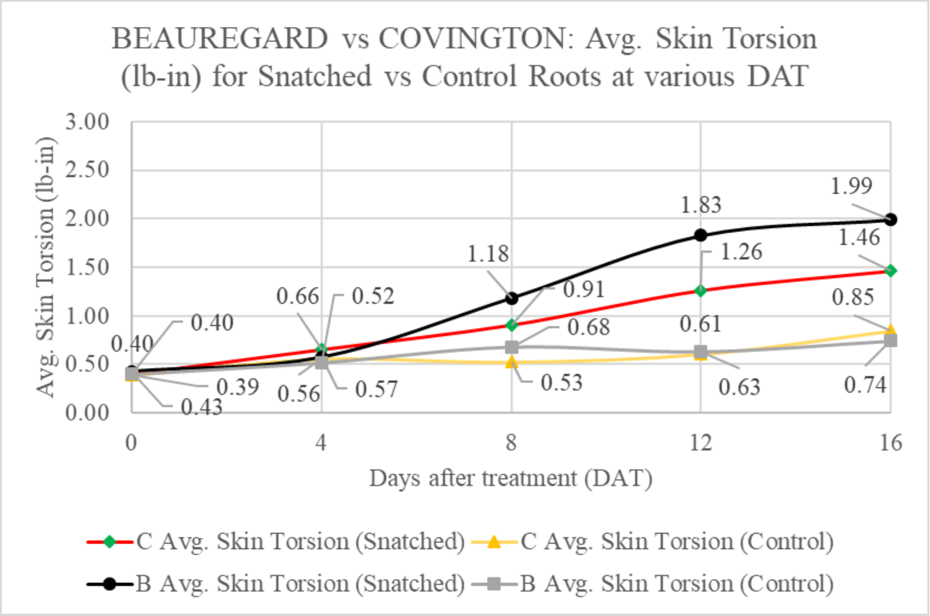


Figure 3.12: Average skin torsion (above) and normal load (below) plots for the three Covington fields for the snatched and control roots with respect to the number of days after using the harvesting aid

17.02 lb for Covington. The maximum average skin torsion for the snatched roots of Beauregard variety was observed to be 1.99 lb-in compared to 1.46 lb-in for Covington. The control roots of Beauregard and Covington varieties, however, seemed to have similar average skin torsion and normal load values over the 16-day period with a maximum average skin torsion of 0.74 lb-in for Beauregard compared to 0.85 lb-in for Covington and a maximum average normal load of 5.89 lb on day 12 for Beauregard compared to 8.17 lb for Covington on day 16.

The average skin torsion and normal load responses for both Beauregard and Covington varieties for snatched and control roots are plotted in Figure 3.13 for direct comparison. The Beauregard variety had a stronger response to the vine-root separation by vine puller-chopper harvesting aid resulting in higher skin torsion and normal load values over the 16-day period for the snatched Beauregard roots compared to the Covington variety. The average skin torsion and normal load responses for the controls roots of the Beauregard variety were similar to the Covington variety over the 16-day period. There might, however, be a slight increase in the skin strength values for the control roots with their vines intact for both Covington and Beauregard varieties over the 16-day period, probably due to a combination of soil moisture and soil temperature values providing a natural curing environment to the roots (Tomlins et al., 2002; Gajanayake et al., 2014; Hayes et al., 2014; Abidin et al., 2016).

Linear mixed effects models were used to analyze the skin strength data from Table 3.1. Models were fit using the MIXED procedure of SAS software (SAS Institute, 2017). Average skin torsion (lb-in) and the average normal load (lb) required to shear the sweetpotato root skin were considered as the response variables. Variety (Beauregard and Covington), treatment (snatched and control (unsnatched)) and DAT (0, 4, 8, 12 and 16 days after being operated by the harvesting aid) were the considered factors. The measured soil temperature (°F), and soil



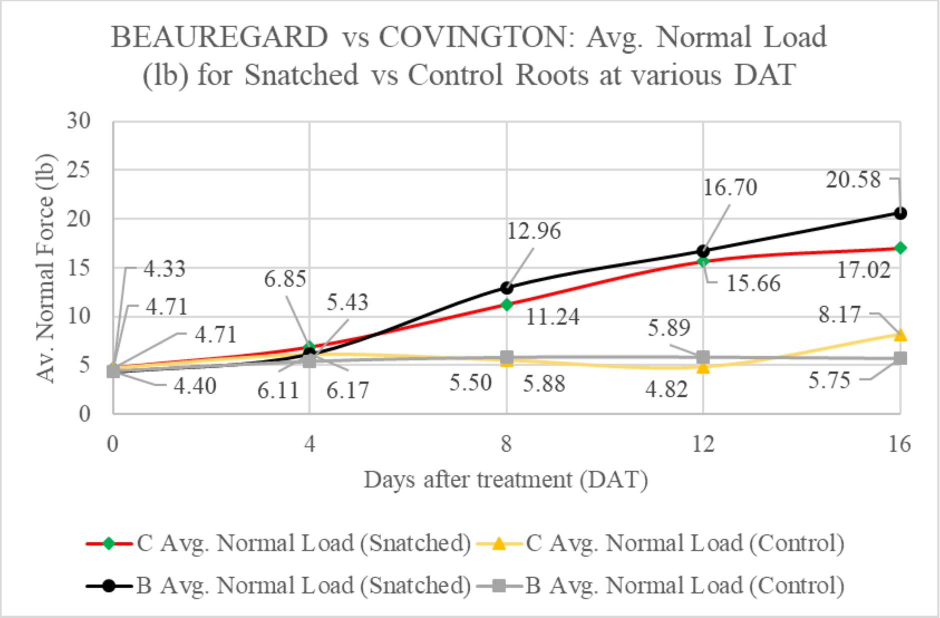


Figure 3.13: Average skin torsion (above) and normal load (below) plots for the three Beauregard and Covington fields for the snatched and control roots with respect to the number of days after using the harvesting aid

moisture (in^3 in^{-3}) were also considered for analysis as variables that may have an effect on the responses. Various editions of the linear models investigated included fixed factorial main effects and interactions involving the factors variety, treatment and DAT. The models also included random effects for plot nested in variety. The soil moisture and soil temperature were included as covariates in the model. Models with higher order interactions did not reveal any significant effects and were not considered further. Models with soil moisture and soil temperature did not reveal any significant effects and were not considered further.

Each of the six fields was considered as a plot with the assigned variety of Beauregard or Covington. A linear mixed effects model was used to investigate factorial effects of interest. In particular, fixed factorial effects were included for treatment, DAT, variety and all interactions among them. As the varieties were assigned to entire plots with varying levels of treatment and DAT on each plot, in a repeated measures design, random effects were included for plot nested in variety. The analysis of variance (ANOVA) for the mixed effects model with the average skin torsion as the response is shown in Table 3.2.

The observed variation across the DAT, treatment and their interaction were significant (p-value < 0.0001) along with the interaction between the variety and treatment (p-value = 0.047). The variability due to the effect of plot nested in variety was not significant in the model (p-value = 0.4296). The assumptions for constant variance and normality were checked using diagnostic plots generated by SAS. Each sweetpotato hill can be considered as independent from other hills. A residuals vs predicted values was plotted (see Appendix B, Figure S5) to check for non-constant variance and a quantile-quantile plot (see Appendix B, Figure S5) was inspected to see if the normality assumption was reasonable.

Table 3.2: ANOVA (Type 3) for the mixed effects model with the average skin torsion as response, fixed factorial effects of variety, DAT, and treatment, and random effect of plot nested in variety

Source	DF	Sum of Squares	Mean Square	Error DF	F Value	Pr > F
Variety	1	0.2774	0.2774	4	5.03	0.0884
DAT	4	5.9661	1.4915	36	26.53	<.0001
Variety*DAT	4	0.2701	0.0675	36	1.20	0.3270
Treatment	1	3.4272	3.4272	36	60.97	<.0001
Variety*Treatment	1	0.2381	0.2381	36	4.24	0.0469
Treatment*DAT	4	2.3283	0.5820	36	10.35	<.0001
Variety*Treatment *DAT	4	0.2931	0.0732	36	1.30	0.2871
Plot (Variety)	4	0.2208	0.0552	36	0.98	0.4296
Residual	36	2.0237	0.0562	.	.	.

The least square means (lsmeans) for selected simple differences of the treatment, DAT interaction (Table 3.3) showed that the pairwise differences for the snatched roots between 0 and 4 days after treatment (p-value = 0.15) as well as between 12 and 16 (p-value = 0.19) days after treatment was not significant. All other pairwise comparisons between the days after treatment for the snatched roots were significant. This tells us that the average skin torsion for the snatched roots are not significantly different for DAT 4 compared to DAT 0 and for DAT 12 compared to DAT 16. The average skin torsion for the control roots (unsnatched) roots was significantly different for DAT 16 compared to DAT 0. All other pairwise differences between DAT's for the control roots were not significant. The lsmeans differences for the treatments at each DAT is

Table 3.3: The lsmeans differences for the treatment with respect to selected days after treatment, average skin torsion as response (Simple Differences of Treatment*DAT LSMEANS)

Slice	DAT	DAT	Estimate	Standard Error	DF	t Value	Pr > |t|
Treatment Snatched	**0**	**4**	-0.2017	0.1369	36	-1.47	0.1494
Treatment Snatched	**12**	**16**	-0.1800	0.1369	36	-1.31	0.1968
Treatment Unsnatched	**0**	**16**	-0.4033	0.1369	36	-2.95	0.0056

shown in Table 3.4. The average skin torsion is significantly different for the roots with their main stems separated by the vine puller-chopper harvesting aid compared to the roots with their vines intact from DAT 8 onwards.

Table 3.4: The lsmeans differences for the treatments at each DAT of 0, 4, 8, 12 and 16 after using the harvesting aid, average skin torsion as response (Simple Differences of Treatment*DAT LSMEANS)

Slice	Treatment	(-) Treatment	Estimate	Standard Error	DF	t Value	Pr > |t|
DAT 0	**Snatched**	**(-) Unsnatched**	0.0200	0.1369	36	0.15	0.8847
DAT 4	**Snatched**	**(-) Unsnatched**	0.0750	0.1369	36	0.55	0.5871
DAT 8	**Snatched**	**(-) Unsnatched**	0.4417	0.1369	36	3.23	0.0027
DAT 12	**Snatched**	**(-) Unsnatched**	0.9233	0.1369	36	6.75	<.0001
DAT 16	**Snatched**	**(-) Unsnatched**	0.9300	0.1369	36	6.79	<.0001

Similar analysis was carried out for the average normal load as the response. Each of the six fields was considered as a plot with the assigned variety of Beauregard or Covington. A linear mixed effects model was used to investigate factorial effects of interest. In particular, fixed factorial effects were included for treatment, DAT, variety and all interactions among them. As the varieties were assigned to entire plots with varying levels of treatment and DAT on each plot, in a repeated measures design, random effects were included for plot nested in variety. The ANOVA for the mixed effects model with the average normal load as the response is shown in Table 3.5.

The observed variation across the DAT, treatment and their interaction were significant (p-value < 0.0001). The variability due to the effect of plot nested in variety was not significant in the model (p-value = 0.27). The assumptions for constant variance and normality were checked using diagnostic plots generated by SAS. Each sweetpotato hill can be considered as independent from other hills. A residuals vs predicted values was plotted (see Appendix B, Figure S6) to check for non-constant variance and a quantile-quantile plot (see Appendix B,

Table 3.5: ANOVA (Type 3) for the mixed effects model with the average normal load as response, fixed factorial effects of variety, DAT, and treatment, and random effect of plot nested in variety

Source	DF	Sum of Squares	Mean Square	Error DF	F Value	Pr > F
Variety	1	1.6401	1.6401	4	0.18	0.6911
DAT	4	547.5432	136.8858	36	20.31	<.0001
Variety*DAT	4	7.7288	1.9322	36	0.29	0.8846
Treatment	1	531.9899	531.9899	36	78.95	<.0001
Variety*Treatment	1	7.8192	7.8192	36	1.16	0.2885
Treatment*DAT	4	364.8055	91.2013	36	13.53	<.0001
Variety*Treatment*DAT	4	20.3815	5.0953	36	0.76	0.5606
Plot (Variety)	4	35.9226	8.9806	36	1.33	0.2766
Residual	36	242.5783	6.7382	.	.	.

Figure S6) was inspected to see if the normality assumption was reasonable. The observed variation among varieties was not significant for both the average skin torsion (p-value = 0.09) and the average normal load (p-value = 0.69). Although we can see from the skin torsion and normal load plots (Figure 3.13) that the Beauregard variety had a higher increase (or a stronger response) in the average skin torsion and normal load values because of vine-root separation by the harvesting aid, we can say from the analysis that the increase is not statistically significant compared to the increase of the observed skin torsion and normal load values for the Covington variety.

The least square means (lsmeans) for selected simple differences of the treatment, DAT interaction (Table 3.6) showed that the pairwise differences for the snatched roots between 0 and 4 days after treatment (p-value = 0.19) as well as between 12 and 16 (p-value = 0.09) days after treatment was not significant. All other pairwise comparisons between the days after treatment for the snatched roots were significant. This tells us that the average normal load for the snatched roots are not significantly different for DAT 4 compared to DAT 0 and for DAT 12 compared to

Table 3.6: The lsmeans differences for the treatment with respect to selected days after treatment, average normal load as response (Simple Differences of Treatment*DAT LSMEANS)

Slice	DAT	DAT	Estimate	Standard Error	DF	t Value	Pr > |t|
Treatment Snatched	**0**	**4**	-1.9850	1.4987	36	-1.32	0.1937
Treatment Snatched	**12**	**16**	-2.6217	1.4987	36	-1.75	0.0888

DAT 16. As a recommendation, growers can harvest the sweetpotatoes 12 days after using the vine puller-chopper harvesting aid instead of waiting for 16 days if there is a shortage of time, as the increase in the average skin torsion as well as the average normal load, as measures of skin strength, between 12 and 16 days is not significant. All pairwise differences between DAT's for the control roots were not significant. The lsmeans differences for the treatments at each DAT is shown in Table 3.7.

Table 3.7: The lsmeans differences for the treatments at each DAT of 0, 4, 8, 12 and 16 after using the harvesting aid, average normal load as response (Simple Differences of Treatment*DAT LSMEANS)

Slice	Treatment	(-) Treatment	Estimate	Standard Error	DF	t Value	Pr > |t|
DAT 0	**Snatched**	**(-) Unsnatched**	-0.03333	1.4987	36	-0.02	0.9824
DAT 4	**Snatched**	**(-) Unsnatched**	0.7383	1.4987	36	0.49	0.6253
DAT 8	**Snatched**	**(-) Unsnatched**	6.4100	1.4987	36	4.28	0.0001
DAT 12	**Snatched**	**(-) Unsnatched**	10.8200	1.4987	36	7.22	<.0001
DAT 16	**Snatched**	**(-) Unsnatched**	11.8417	1.4987	36	7.90	<.0001

The average normal load is significantly different for the roots with their main stems separated by the vine puller-chopper harvesting aid compared to the roots with their vines intact from DAT 8 onwards (p-value < 0.0001). As a recommendation, growers need to harvest the sweetpotatoes no less than 8 days after using the vine puller-chopper as a pre-harvest operation for a significant increase in the average skin torsion and average normal for the roots which is an overall increase in the skin strength.

3.5. Summary and Conclusions

Results from these studies showed that skin strength of the sweetpotato roots increased as early as 4 days after achieving complete vine-root separation by the vine puller-chopper harvesting aid for the Beauregard and Covington varieties. However, a skin setting period of 8 days after using the vine puller-chopper harvesting aid significantly increased the sweetpotato skin strength irrespective of the variety. The growers should allow a period of 8 days to set the skin and increase the skin strength after operating the vine puller-chopper harvesting aid before they harvest the roots to reduce root damage during harvesting. There was an overall increase in skin strength for the snatched roots compared to the skin strength for roots with their vines intact over the 16-day period for both the Covington and Beauregard varieties. Numerically, Beauregard variety had higher maximum average skin torsion and normal load values of 1.99 lb-in and 20.58 lb for the snatched roots compared to 1.47 lb-in and 17.02 lb for the Covington variety. Although, statistically insignificant, Beauregard showed a slightly stronger response to the vine-root separation over the 16-day period compared to the Covington variety.

Soil moisture and soil temperature didn’t seem to have any significant effect or consistent response on the skin setting for both varieties. However, the right combination of soil moisture and soil temperature that corresponds to the humidity and temperature used during curing of the sweetpotatoes may provide a natural curing environment for the roots (Tomlins et al., 2002; Gajanayake et al., 2014; Hayes et al., 2014; Abidin et al., 2016) below the soil and enhance the skin strength as there were instances of the soil moisture and temperature’s interaction apparently having an influence on the skin strength responses of the sweetpotatoes. In particular, treatment combinations including soil moisture, soil temperature of (0.095 in^3 in^{-3}, 75°F), (0.245 in^3 in^{-3}, 62°F), (0.068 in^3 in^{-3}, 64°F) and (0.08 in^3 in^{-3}, 61°F) can be studied in the future as these had a negative effect on the skin strength for some instances. The increased skin strength due to the vine-root separation by the harvesting aid would help reduce the skinning damage to the roots during mechanical harvesting, transport and processing. Quantification of the skin torsion and normal load as a measure of skin strength from this study would help better design the sweetpotato mechanical harvesting equipment to further reduce root damage, thus allowing for mechanically harvested roots for fresh market sales in the future.

The quantification of the skin strength for the roots corroborated the hypothesized skin setting process in response to the removal of vines as suggested by several authors in literature (Dukuh, 2011; Arancibia et al., 2013; Wang et al., 2013; Hayes et al., 2014). The vine-root separation also serves the purpose of controlling root growth and given enough time and the appropriate soil moisture and temperature, may even serve as a natural curing environment (Tomlins et al., 2002) for the roots below the soil. The skin strength data obtained in this study corroborates previous research done by Legendre (2014) who found that a shear force of approximately 2.21 lb-in is required to remove the skin after defoliation. Hayes et al. (2014) required a torque of approximately 1.5 lb-in to shear the root skin of Beauregard and Evangeline varieties 6 days after undercutting them. Legendre (2014) observed skinning resistances of approximately 2.1 lb-in using a modified torque wrench for the Beauregard variety. Skinning tests by Hammerle (1970) resulted in a normal force equivalent to 3 to 14 lb for the Centennial sweetpotato variety. Fluck et al. (1968) observed forces equivalent to around 12 lb for Centennial variety of sweetpotatoes with the normal force dropping by around 1 lb during curing and then increasing back the 1 lb during storage over 10 months. Wright and Splinter (1968) evaluated the average rupture force values for different varieties of sweetpotatoes to be in the range of 11 lb to 20 lb during the time of harvest.

The roots are subjected to around 120 psi at a normal load of 4.5 lb during post-harvest handling such as curing according to Fluck et al. (1968). The psi values obtained in this study to shear the snatched roots' skin were in the range of 130 psi for Beauregard and 100 psi for Covington at the end of the 16-day period. A water pressure of around 90 psi was required to skin the Beauregard variety according to Villavicencio et al. (2004) which is also in the range obtained in this study. Edmunds et al. (2008) listed water pressures of around 250 psi and an impact load of 8 to 25 lb during post-harvest handling such as packing and grading. Further curing of the roots after this study would be sufficient to bear the pressures and loads listed by Edmunds et al. (2008). Bird (2015) evaluated the shear and tensile force for different sweetpotato cultivars and observed a shear force up to 2.6 lb-in for roots which were de-vined 7 days prior to harvest. According to puncture and deformation tests done by Bourne (1966) on various commodities, the shear coefficient of uncooked sweetpotato was observed to be around 0.90 kg-cm (~5 lb-in) and the compression coefficient for the same was observed to be around 20 kg.cm^2 (~6.8 lb-in^2). These comparisons to the previous research done by other authors shows that our study was consistent and relevant in the context of sweetpotato root skin strength measurement.

Further research beyond this study can evaluate if there are any benefits from the curing process in terms of energy and cost reduction. Since we are increasing the skin strength and providing near natural curing environment to the roots for up to 16 days before they are harvested, it is possible that this may reduce the energy and costs associated with the curing process for these roots. Oluwo et al. (2013) reported that in general the skin had a positive effect on the thermal properties calculated for both white potatoes and sweetpotatoes. Thermal properties available in the literature prior to the research conducted by Oluwo et al. (2013) were without the skin. Oluwo et al. (2013) reported that between sweetpotatoes and white potatoes, the sweetpotatoes had a larger specific heat capacity compared to white potatoes. This means that they can store more energy before their temperature rises implying that the curing process for sweetpotatoes would require more energy. Maybe a combination of the thermal properties and the mechanical properties can yield a more energy saving curing process. Also, the soil moisture in further studies might be controlled to emulate the curing relative humidity to determine if the skin strength is further increased when the snatched roots are left in the soil.

Ndunguru et al. (2000) found that the percentage of roots damaged during harvesting with cuts and abrasions were around 30%, with major skinning injuries around 10%. La Bonte and Wright (1993) quantified the reduction in skinning injury because of pre-harvest canopy removal to be around 60% when the vines were mowed 10 days before harvest and decreased linearly to around 25% when mowed 4 days before harvest. Further studies should continue to investigate if the increased skin strength due to the vine-root separation by the vine puller-chopper harvesting aid significantly reduced damage during harvesting and post-harvest handling. Due to the limited time and resources for this project we had to limit the scope of our study to only the pre-harvest operation of vine-root separation by the harvesting aid. Sweetpotato varieties with a tougher skin to avoid injury and damage during harvesting are yet to be evaluated for their acceptance in the market.

One important consideration from this research that needs to be investigated in the future is the influence of the skin toughening, as a result of the vine-root separation using the harvesting aid, on the chemical quality of the sweetpotatoes. Chemical analyses of the starch and sugar content, for example, may be useful to give a holistic viewpoint. Dukuh (2011) observed that sprouting of the roots increased up to five times for the roots that were defoliated 12 days prior to harvest compared to roots that were not defoliated, thus this response may reduce sweetpotato quality. Nabubuya et al. (2017) found that curing increased sucrose and glucose content by approximately 10% and 1% respectively, and reduced starch by approximately 50%. With the skin strength enhancement due to vine-root separation, it is possible that these values may be different and can be investigated in the future.

The sweetpotato equipment of the future for mechanical harvesting and post-harvest handling should be designed such that the forces acting on the sweetpotato roots during handling are less than the forces required to cause damage. Quantification of the skin strength of the sweetpotato roots at the time of harvest in response to vine separation from the roots was well documented in this study. Exploring vine-root separation prior to harvest, preferably at least 8 days, should be useful for growers as well as the sweetpotato equipment manufactures in the future.

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CHAPTER 4: Economic Study of Harvesting Scenarios Involving the Vine Puller-Chopper Harvesting Aid

4.1. Abstract

A two-row sweetpotato vine puller-chopper harvesting aid was developed and its performance in relation to achieving complete vine-root separation was analyzed. The increase in skin toughness due to detachment of the main stem from the roots by the harvesting aid was quantified over a 16-day period prior to harvest and determined to be a viable and beneficial pre-harvest machine for sweetpotatoes. Simple economic studies of current harvesting scenarios involving the developed harvesting aid were assessed. Current harvesting practices in North Carolina include the roots being turned over by a disc plow or a chain digger and hand-collected for fresh market use, or the roots being dug using an available commercial mechanical digger for the processing industry. A pre-harvest mowing operation is common practice using commercially available flail mowers, especially when using a chain digger or a mechanical digger for digging the roots, to control root growth, reduce the amount of vine and exclude soil in the harvested crop. Harvesting scenarios were studied using the vine puller-chopper as a pre-harvest operation in terms of harvesting efficiency, time required to harvest, the labor required, the level of drudgery involved in terms of number of instances the farm crew had to reach out to separate the vines from the roots, along with the associated partial machine and labor costs. This was compared to a flail mower using the same criteria, which included the roots being (i) chain dug and hand-collected, (ii) disc plowed and hand-collected, and (iii) dug by a commercial mechanical harvester. The vine-root separation by the vine puller-chopper harvesting aid emerged as a feasible and better alternative to the current pre-harvest mowing operation for both fresh market and processing roots. The current harvesting practice of using a disc plow as a

mechanical aid, with no pre-harvest vine removal operations, was deemed to be the most economical with the available technology. However, there is potential for the vine puller-chopper harvesting aid to be involved in a future harvesting scenario to economically compete with the current disc plow harvesting practice.

4.2. Introduction

In the United States (US) more than 80% of the sweetpotatoes that are harvested are used for human consumption and the remaining for processed products and other uses (Lebot, 2009). Sweetpotato as a food source is gaining popularity, especially in the US. People are eating more sweetpotatoes because of its nutritional benefits (Burri, 2011). Sweetpotatoes are not only a source of many nutrients including pro vitamin A carotenoids, vitamin C, zinc, manganese and iron but are also rich in anti-oxidants and fiber (Burri, 2011). In addition to vitamins, sweetpotatoes are a good source of minerals and fibers (Arancibia et al., 2018). Sweetpotato is a major crop grown throughout the tropical and sub-tropical world. China is the largest producer of sweetpotatoes (Truong et al., 2018) with the US producing over 35 million cwt (hundredweight) in 2017 (USDA-NASS, 2018), which is less than 1% of world production (Truong et al., 2018).

In the United States, sweetpotatoes are grown for its roots which are, until very recently, a traditional holiday food. Over 150,000 acres of sweetpotatoes were harvested in 2018 in the US (USDA-NASS, 2018) with North Carolina producing approximately 60% of the country’s crop with a production value over $340,000,000 (USDA-NASS, 2017). The overall sweetpotato consumption in the country increased by approximately 90% in the last 15 years (Johnson et al., 2015) with the per-capita consumption being close to 8 pounds in 2017 (Statista, 2017). Sweetpotatoes in North Carolina are generally grown in sandy coastal plain soils. North Carolina has witnessed over a 200% increase in production in the last 15 years. In 2018 approximately

90,000 acres were harvested in North Carolina with an average yield of 220 cwt acre^{-1} (USDA-NASS, 2018). The Covington variety developed by Yencho et al. (2008) accounts for over 90% of North Carolina acreage (Smith, 2018). Average Beauregard yields were approximately 150 cwt acre^{-1} over the last 30 years with approximately 70% of them being US No. 1 (Villordon et al., 2010). In North Carolina, the Covington crop produced an average total yield of approximately 325 cwt acre^{-1} and Beauregard crop approximately 360 cwt acre^{-1} (Yencho et al., 2008).

Studies on chemical compositions of leaves, vines and roots conducted by Frankow-Lindberg and Lindberg (2003), Anital et al. (2006), Truong et al. (2007), and Dako et al. (2016) can serve as important information when evaluating the possibility of obtaining value added products such as biofuels from sweetpotatoes, implementation of which are currently limited by the processing costs and conversion efficiency (Schweinberger et al., 2016). The sweetpotato processing industry has expanded substantially in the last few years. The utilization of sweetpotatoes for alternative markets such as processed foods, biofuels and other industrial products is limited due to high costs of production which are a direct consequence of high labor inputs (George et al., 2011). Viability of new markets for sweetpotatoes will need the production costs to be lowered (George et al., 2011).

Approximately 75% of North Carolina’s sweetpotato crop is sold as a fresh market produce, while the remaining sweetpotatoes are harvested with the intention of selling them as processed or canned foods or using them as seed stocks (Lucier et al., 2002). Production costs for sweetpotatoes in the United States are in the range of $2,000 per acre to $4,000 per acre depending on several factors including region and farm size (Clark et al., 2010; George et al., 2011). North Carolina utilizes approximately 8,000 H-2A workers a year to harvest crops of cucumber, tobacco and sweetpotato at approximately 1,000 farms (Cabanillas, 2006). It costs approximately $2,000 to hire one H-2A worker for an average 4-month contract period for harvesting which includes worker recruitment costs, housing, transportation and excludes the $11.46 minimum hourly wage rate (Roka et al., 2017). Farm labor wages are on the rise from 1990 at an average rate of 0.8% per year with more than 80% of the farm labor being of an origin other than United States (Zahniser et al., 2011). Sweetpotato growers need to minimize the production costs and increase yields to overcome the challenge of producing a profitable crop to meet future demands (Schultheis et al., 1999). Empirically, labor plays a significant role in determining the profitability in sweetpotato production (Adewumi and Adebayo, 2008; Tewe et al., 2003) and is almost as much as the planting material and fertilizer inputs into the process. Labor accounted for approximately 68% of the sweetpotato production costs in a study conducted by Kassali (2011) with data from over 90 growers. Approximately 40% of the total labor required for sweetpotato production is related to harvesting (Guidry et al., 2019).

All produce is sold primarily by appearance with sweetpotatoes being no exception. Sweetpotatoes intended for fresh market purposes are generally hand harvested to reduce root damage and to maintain shelf life and appearance which is of utmost importance to compete in the market. In context, the sweetpotatoes destined for processing can be potentially harvested with available commercial diggers so that more acreage can be harvested in less time as there is less importance to the quality and appearance of the sweetpotato. Unfortunately, the harvesting machines available commercially for fresh market sweetpotatoes are either semi-mechanized, with no significant reduction in labor or are rarely completely mechanized. These can generally be used only for processed or canned produce due to the unacceptable levels of damage that they cause to the sweetpotato roots (Hammerle, 1970). Mechanical diggers cause excessive and unacceptable skinning damage to the sweetpotato roots. For this reason, most of the sweetpotatoes are still turned over by a plow and harvested manually by a harvesting crew (Srinivas, 2009). A harvesting aid was developed by Zahara and Scheuerman (1969) which conveyed the dug roots past labor on trailers. Workers were required to separate the roots from the main stem and guide the sweetpotatoes to the bins. The harvest aid was an alternative method to conventional hand harvesting and was observed to reduce labor requirement by approximately 40% for the harvesting operation in terms of the reduced time required for the deposition of sweetpotato roots into the bins. Harvesting aids, such as the one developed by Zahara and Scheuerman (1969), which dig the roots and conveyed them by elevating the roots onto a horizontal working platform allowed for laborers to perform the same task of separating individual roots from the main stem by snapping them and reduced the drudgery involved with hand harvesting (Abrams et al., 1978). Flores (2018) analyzed a small-scale one-row conveyor-digger as a harvesting aid to reduce harvesting losses and labor cost. Flores (2018) observed that the conveyor-digger could reduce damage during harvesting, increase the salable fresh market roots by at least 10% and reduce the labor costs by 50%.

The study on the vine puller-chopper harvesting aid developed in the course of this investigation would be incomplete without an economic perspective on the research done for the betterment of the harvesting process. Ultimately it is the costs and returns that drive the farmers to grow a crop. An economic study of newly developed technology can provide a better understanding of the benefits and flaws of adopting the technology. Increase in demand and farm wages are driving the enabling of mechanical harvesting of sweetpotatoes in the future. The vine puller-chopper harvesting aid was developed to assist and improve mechanical harvesting in the future by achieving complete vine-root separation prior to harvest. The performance of the harvesting aid in achieving vine-root separation and its impact on the enhanced skin strength of the roots prior to harvest was covered in the previous chapters. A simple economic study of the harvesting aid developed was conducted in conjunction with the current North Carolina harvesting practices. Harvesting scenarios were studied using the vine puller-chopper as a pre-harvest operation in terms of harvesting efficiency, time required, labor required, drudgery involved and associated partial machine and labor costs, in comparison to a flail mower for the same purpose, which included the roots being (i) chain dug and hand-collected, (ii) disc plowed and hand-collected, and (iii) dug by a commercial mechanical harvester. The objective of the study was to assess the benefits and feasibility of using the vine puller-chopper harvesting aid as a pre-harvest operation with the current North Carolina harvesting practices in terms of labor required, harvesting efficiency and related costs.

4.3. Methodology

Common harvesting practices in North Carolina for fresh market sweetpotatoes include the roots being turned over to the side of the rows by a disc plow and hand-collected by a farm crew. Some growers use a chain digger to dig the roots and place them on top of the soil for a farm crew to pick them up and place them into bins. A few growers also use available commercial diggers for sweetpotatoes destined mostly for processing that deposit the roots being dug into bins through a conveyor mechanism. Typically, the vine material is mowed using commercially available flail mowers which help reduce the vine interference with the harvesting equipment, especially when using the chain digger and the mechanical digger. When using a disc plow as the harvesting equipment, the mowing operation may or may not be done at the discretion of the grower. Pre-harvest mowing is also done to control root growth and to reduce damage due to the vines and soil clods during harvesting (Hayes et al., 2014).

All the fields available for testing were at Burch Farms, Faison, NC in the harvesting seasons of 2016 and 2017 and were grown with customary cultural practices (Schultheis et al., 1999; Meyers et al., 2010). A one-acre plot of the Averre variety consisted of 32 rows approximately 250 ft long with a 40-inch row spacing and a 13-inch in-row plant spacing in the 2017 harvesting season. The two-row vine puller-chopper was operated at 2.2 mph with previously established optimum machine parameters for the mower (1200 rpm) and pinch-roller (180 rpm) speeds on 16 rows in the field. These 16 rows were dug using a conventional two-row chain digger (Figure 4.1) which required removal of the vines prior to harvest. The chain digger placed the roots on top of the soil for the farm crew to pick up and place in the bins.

Figure 4.1: The field with the Averre variety being operated by the vine puller-chopper harvesting aid (left), the roots being dug by the chain digger (center) and being hand-collected by a farm crew (right) at Burch Farms, Faison NC, during the 2017 harvesting season

The roots in the other 16 rows of the field were turned over using a conventional 8-row disc plow. There was no pre-harvest operation done to remove the vines before using the disc plow. The same harvest crew of 24 members were asked to pick up the roots for both sections of the field and place them into the bins. The time required to complete the harvesting operation including the pre-harvest runs by the vine puller-chopper harvesting aid were recorded. The yield of each section of the field was also recorded in terms of the number of 40-bushel bins that were filled. There were no severe damage instances to the roots by any of the pre-harvest or harvesting equipment and thus were not considered as part of the evaluation of the harvesting scenarios. A CASE 125 MAXXUM tractor was used for all the harvesting operations.

A separate field of the Beauregard variety of approximately four acres was available for testing in the 2016 harvest season which was mechanically dug for processing using a commercial sweetpotato mechanical digger (STANDEN TSP 1900, Farmers Harvest Inc., Camden, NC). The field consisted of rows approximately 500 ft long with a 40-inch row spacing and a 13-inch in-row plant spacing. Sixteen rows of the field were barred off from the center of the field using the “caution” barricade tape and the rows were marked using flags. The two-row vine puller-chopper harvesting aid was operated on eight rows (approximately half acre) and the other eight rows were mowed using a 4-row flail mower (BRC115, Bush Hog, Smithfield, NC) to make it equivalent to the field area of approximately half acre for consistency. All the rows were mechanically dug with two members of the farm crew on the conveyor system of the digger to separate the vines from the roots before being deposited in the bins (Figure 4.2).

Figure 4.2: The field with the Beauregard roots being mechanically dug (left) and conveyed into the bins (right) by the STANDEN TSP 1900 sweetpotato mechanical digger during the 2016 harvesting season at Burch Farms, Faison NC

The time required to complete the harvesting operations including the pre-harvest runs by the vine puller-chopper and the flail mower were recorded. The yield for each section of the field was recorded by counting the number of 40-bushel bins harvested. The number of instances both members of the farm crew reached out and separated the vines from the roots on the conveyor system was noted for each section of the field as a comparison of the level of drudgery involved during harvesting between the flail mower and the vine puller-chopper harvesting aid as a pre-harvest operation. A simple economic comparison of all the harvesting scenarios was done to assess the feasibility of the vine puller-chopper harvesting aid with the current harvesting practices.

4.4. Results and Discussion

For the half-acre study with the Averre variety where the vine puller-chopper was used as a pre-harvest operation and the roots were chain dug and hand-collected with a farm crew of 24 members, the following observations were made:

Time taken by the harvesting aid = 12 min

Time taken by the chain digger = 34 min

Time taken for hand picking the roots = 18 min

Yield = 6 bins of 40 bushels each = 240 bushels

For the half-acre section of the study with the Averre variety where the disc plow was used to turn the roots before hand picking them without any pre-harvest operation, the following observations were made:

Time taken by the disc plow = 6 min

Time taken for hand picking the roots = 20.6 min

Yield = 6 bins of 40 bushels each = 240 bushels

For the half-acre section of the study with the Beauregard variety where the vine puller-chopper was used as a pre-harvest operation and the roots were mechanically dug, the following observations were made:

Time taken by the harvesting aid = 14 min

Time taken by the mechanical digger = 20 min

Yield = 7 bins of 40 bushels each = 280 bushels

Instances where the crew members reached out to separate the vines from the roots on the conveyor system = 48

For the half-acre section of the study with the Beauregard variety where the vine puller-chopper was used as a pre-harvest operation and the roots were mechanically dug, the following observations were made:

Time taken by the flail mower = 10 min

Time taken by the mechanical digger = 20 min

Yield = 7 bins of 40 bushels each = 280 bushels

Instances where the crew members reached out to separate the vines from the roots on the conveyor system = 179

It was also observed that in this case, the members of the farm crew were unable to keep up with the conveyor speed and some of the roots were sent to the bins with the vines intact and some soil clods being carried with them.

Results from the study were extrapolated for an acre of the field. For the harvesting scenario using the vine puller-chopper harvesting aid and chain digger, the 24-member crew hand-collected the roots from the half-acre field in 18 minutes → 24 members would hand-collect one acre in 36 minutes. With the same calculations, the same 24-member farm crew required 41.2 minutes to hand-collect roots from a one-acre field that were turned over by a disc plow, assuming they had the same work rate in both harvest scenarios. For the farm crew to hand-collect the roots turned by the disc plow in the same time they collected the roots that were separated by the vine puller-chopper harvesting aid and chain dug, i.e. 36 minutes, it would take

24*41.2/36 members → 27.5 ~ 28 members, four more members than the harvesting scenario involving the vine puller-chopper harvesting aid.

The total operating time in terms of the machinery for each harvesting scenario were calculated to be 92 min per acre using the vine puller-chopper and the chain digger with an additional 36 min per acre for hand-collecting the roots, 12 min per acre for the disc plow with an additional 42 min per acre for hand-collecting the roots, 68 min per acre for the harvesting aid followed by the mechanical digger with the roots being automatically deposited in the bins during that time, and 60 min per acre for the flail mower followed by the mechanical digger with no additional time for depositing the roots into bins. The time taken for each harvesting scenario, by itself, is not a limiting factor for the grower, but it can be manifested into the equipment costs required for each harvesting scenario.

The equipment costs per acre in each of the harvesting scenarios were calculated using the worksheet to estimate farm machinery costs provided by Edwards (2015). The cost of the vine puller-chopper harvesting aid was estimated at $40,000. The Bush Hog BRC115 series row-crop flail shredder (flail mower) was priced at $25,000. The conventional disc plow cost approximately $15,000 while the conventional chain digger was valued at $20,000. The sweetpotato mechanical digger was valued at $250,000. The economic life was assumed to be 8 years for all the machinery and no accumulated hours were considered. The interest rate, annual use hours, fuel price, and taxes were assumed to be constant for all the scenarios. All other associated costs with the growing practices such as costs related to seed, bulk bins, transplant machinery, labor, fertilizer, herbicide and other land and management costs were assumed to be the same for each harvesting scenario. The machine costs involved in each harvesting scenario with the ownership costs, the operating costs and the field capacity were considered to estimate the total machinery costs for each harvesting scenario.

The disc plow total machinery costs, excluding the costs associated with the machinery involved with the harvest bins and their logistics (which was assumed to be similar for each harvesting scenario), was approximately $96 for the tractor + $25 for the plow per hour which totaled to approximately $121 per hour and manifested into $24.2 per acre based on the field capacity of the plow. For the harvesting scenario involving the vine puller-chopper followed by the chain digger, $96 was required for the tractor per hour and $61 per hour ($62.8 per acre) for the harvesting aid with $33.5 per hour ($145.2 per acre) for the chain digger which amounted to a total of approximately $286.5 per hour and manifested into $208 per acre if using separate tractors for each machine. For harvesting scenarios involving the mechanical digger along with the vine puller-chopper harvesting aid, the costs were estimated at $96 per hour for the tractor with $61 per hour for the harvesting aid and $362.5 per hour for the mechanical digger which manifested into $215.6 per acre. The harvesting scenario where the flail mower was used with a mechanical digger resulted in a cost of $42 per hour for the flail mower in addition to the tractor and mechanical digger costs, amounting to a total cost of approximately $192.3 per acre.

The associated hand-collecting labor costs were estimated at an additional four crew members per acre when using a disc plow compared to the labor required per acre when using the vine puller-chopper harvesting aid with a chain digger. According to Roka et al. (2017) it costs approximately $2,000 to hire one H-2A worker for an average 4-month contract period for harvesting which includes worker recruitment costs, housing and transportation and excludes the $11.46 minimum hourly wage rate. It was assumed that 100% of the workers were hired on a H-2A work permit. Assuming that a hired farmworker is utilized for the entire four months of harvesting and spends approximately 100 days of work with 9 hours a day, the cost of hiring per hour for each new farm crew member would be \$2,000/900 = \$2.23 per hour. Medicare, workman's compensation and social security costs amount to at least 25% of the minimum wage rate according to Guidry et al. (2019). Adding these costs to the minimum wage rate and the cost per hour of acquiring the farm crew member results in approximately \$17 per hour for each new labor. Since we estimated that roots from a one-acre field would be hand-collected in approximately 36 mins, the costs per acre associated with four new members per acre would be 17*4/(60/36) = \$40.8 per acre.

The yield per acre of the Averre variety for fresh market use was estimated at 480 bushels per acre = 24,000 lb acre^{-1}. Assuming that a 40-lb carton of hand-collected sweetpotatoes sold for approximately \$18, we have the output per acre to be approximately \$10,800. The mechanical digger for the Beauregard variety was used as the roots in those fields were being sent for processing. Assuming that the roots being sent for processing were priced at \$10 for a 40-lb carton, the total yield per acre was approximately 560 bushels per acre = \$28,000 lb acre^{-1} which would result in \$7,000 per acre worth output from the sweetpotatoes.

4.5. Summary and Conclusions

A comparison of the harvesting scenarios in terms of the output of the storage roots and the calculated partial costs associated per acre for the sweetpotatoes was done. When the vine puller-chopper was used as a pre-harvest operation and the roots were dug with a chain digger and hand-collected, it reduced the time required to collect the roots and place them into bins due to the vine-root separation achieved by the harvesting aid. A partial added cost of \$62.8 per acre was estimated with the use of the vine puller-chopper harvesting aid amounting to a total partial cost of \$208 per acre for using the harvesting aid and the chain digger with the chain digger having a partial added cost of $145.2 per acre. The partial cost where the roots were turned over by the disc plow and hand-collected was approximately $24.2 per acre. An added labor cost of $40.8 per acre was attributed in this case compared to the harvesting scenario of the vine puller-chopper being used with a chain digger to hand-collect the roots.

In the case of using the mechanical digger to harvest the roots for processing the two scenarios with the vine puller-chopper and a flail mower in pre-harvest operations resulted in partial costs of $215.3 and $192.3 per acre, respectively. However, the harvesting scenario with the harvesting aid had more than 350% increase in instances where the farm crew on the conveyor system had to reach out to separate the vines from the roots. Also, several of the root hills deposited included the vines and soil clods (Figure 4.3) along with them into the harvest bins potentially resulting in loss of yield.

Figure 4.3: The soil clods (left) and vines (right) being deposited along with the mechanically dug Beauregard roots for the harvesting scenario involving a flail mower as a pre-harvest operation in comparison to using a vine puller-chopper (circled) during the 2016 harvesting season at Burch Farms, Faison NC

An indirect impact of the harvesting aid would be its impact on health and safety with less hazards due to less instances of reaching out to separate the vines from the roots on the conveyor system. Hayes et al. (2014) suggest that this kind of deposition of vines and soil clods in the bins during harvesting would cause major issues in handling, transport, cleaning and grading of the roots. In addition, the vines and soil would add to the weight of the field trucks and reduce the efficiency of harvesting. The vine puller-chopper harvesting aid is a more economical alternative to the flail mower being used as a pre-harvest operation whether it is for fresh market sweetpotatoes or roots meant for processing with an added cost per acre of < $20 compared to the flail mower, but with several benefits in terms of the harvesting quality of the sweetpotatoes. The disc plow being used with no pre-harvest vine removal operation is the most economical of the current harvesting scenarios and it is the most common harvesting practice currently being used. The chain digger had a very high partial cost of almost six times that of the disc plow. The partial added costs due to the vine puller-chopper as a pre-harvest operation ($62.8 per acre) was more than twice the partial cost associated with the disc plow ($24.2 per acre); however, with an added labor requirement using the disc plow ($40.8 per acre), the partial cost using the vine puller-chopper harvesting aid was nearly similar to the disc plow in terms of net added costs due to the equipment. However, the vine puller-chopper only separates the vines from the roots and leaves the roots separated beneath the soil with no turning of the roots on top of the soil to pick them up, thus requiring two field operations.

The harvesting scenario using the vine puller-chopper as a pre-harvest operation and the disc plow to turn the roots so they could be picked up by the hand crew was qualitatively analyzed (Figure 4.4). It was observed that due to vine-root separation by the harvesting aid,

Figure 4.4: A harvesting scenario using the vine puller-chopper as a pre-harvest operation and turning the Averre roots over by a disc plow (circled) in comparison with no pre-harvest operation during the 2017 harvesting season at Burch Farms, Faison NC

many of the roots are scattered and lie beneath the soil surface as it is turned by the disc plow. This makes it difficult for the farm crew to locate and collect the roots resulting in loss of yield and more cost.

The disc plow used was an 8-row unit whereas the vine puller-chopper harvesting aid and the chain digger were two-row units. Having a 4-row vine puller-chopper harvesting aid and a 4-row chain digger would reduce the costs associated with the harvesting operation and potentially be monetarily more competitive with the current harvesting practice involving the disc plow. Further development to the vine puller-chopper harvesting aid with a provision for turning over the roots along with achieving vine-root separation would be an ideal case to significantly improve the current harvesting practice in terms of efficiency and costs. The vine puller-chopper harvesting aid can be a viable option in the future due to a labor shortage and highly expensive farm wages. The potential reduction in production costs and labor requirements in producing sweetpotatoes can also make sweetpotatoes more financially competitive and be used in alternative end uses as they are developed in the future. With the demand for sweetpotatoes increasing, and potential labor shortage and an associated increase in expenses, mechanical harvesting will need to be a viable option for sweetpotato production for fresh market. The vine puller-chopper harvesting aid was developed to help overcome some of the obstacles encountered with mechanical harvesting of sweetpotatoes, successfully.

4.6. References

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APPENDICES

Appendix A

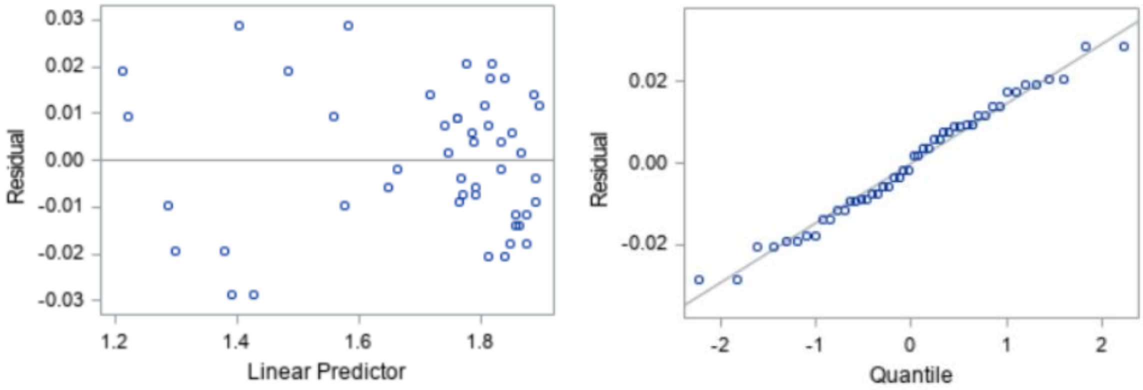

Figure S1: Diagnostic plots for the model with log transformed separation efficiency as response

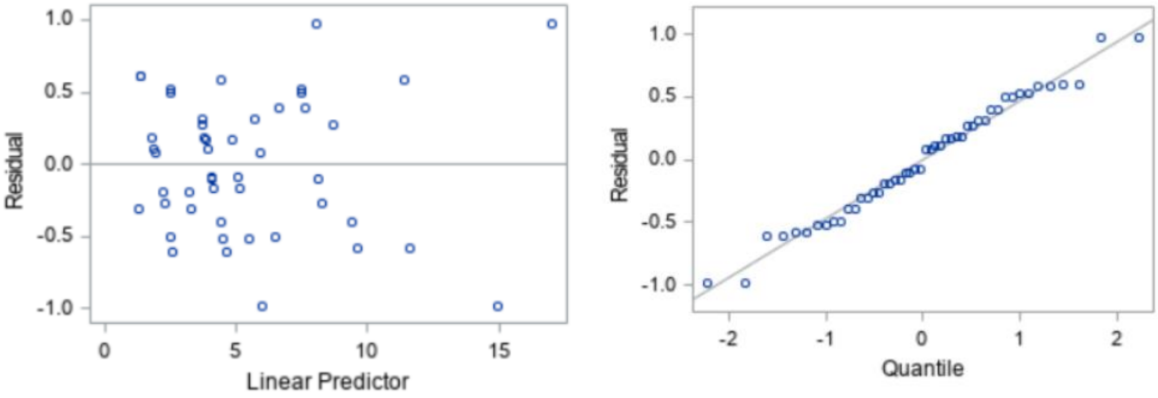

Figure S2: Diagnostic plots for the model with percentage damaged as response

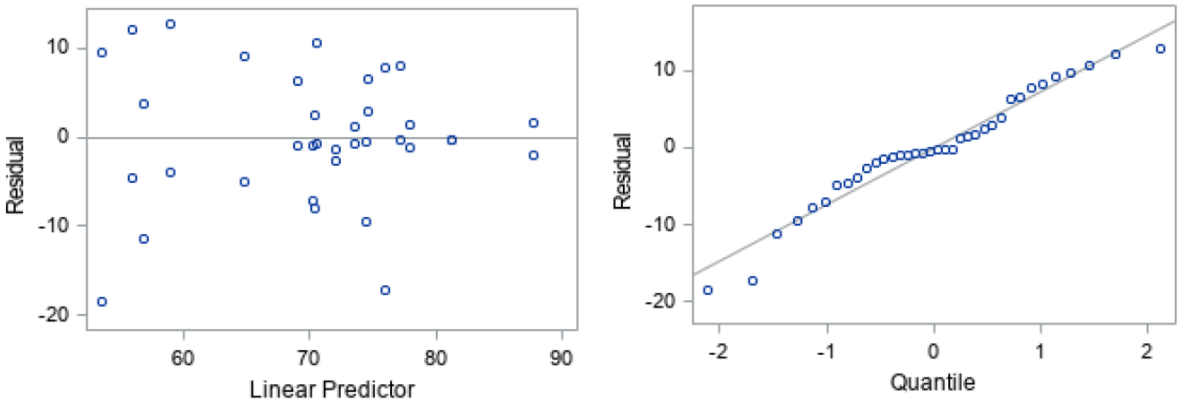

Figure S3: Diagnostic plots for the model with separation efficiency as response

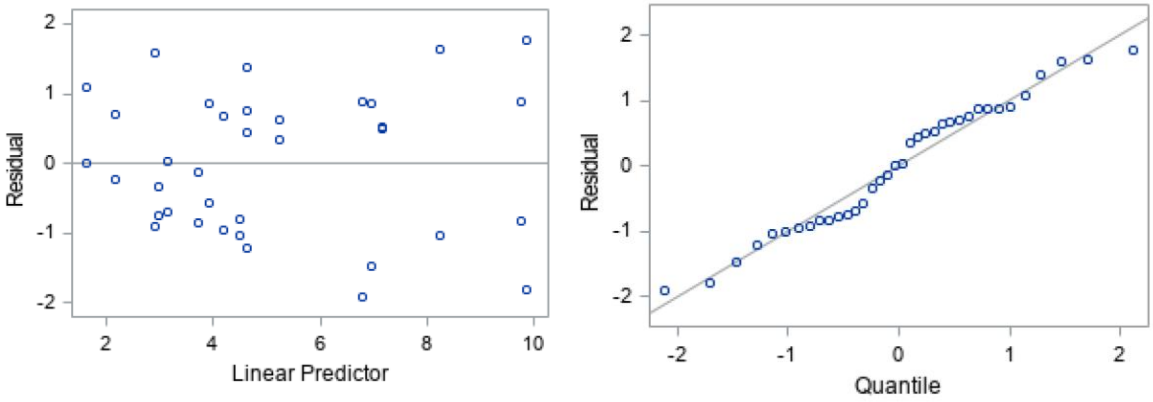

Figure S4: Diagnostic plots for the model with percentage damaged as response

Appendix B

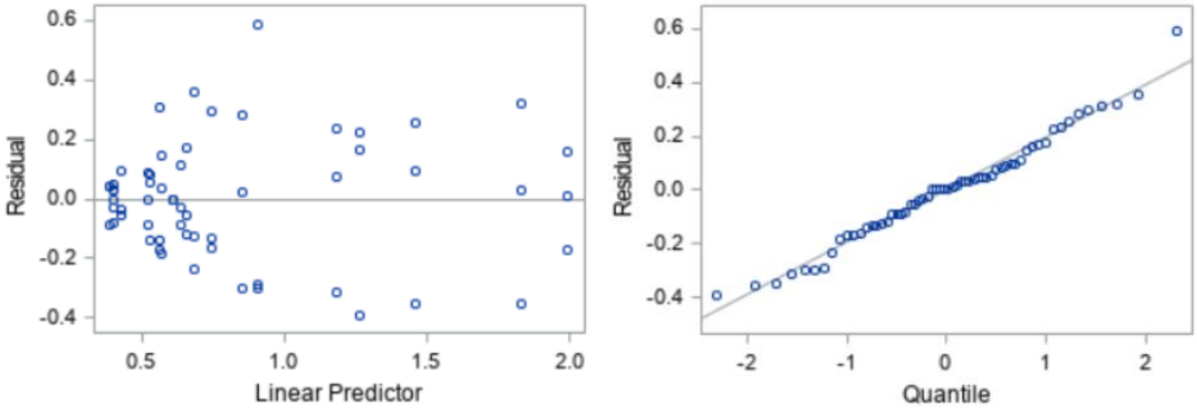

Figure S5: Diagnostic plots for the model with average skin torsion as response

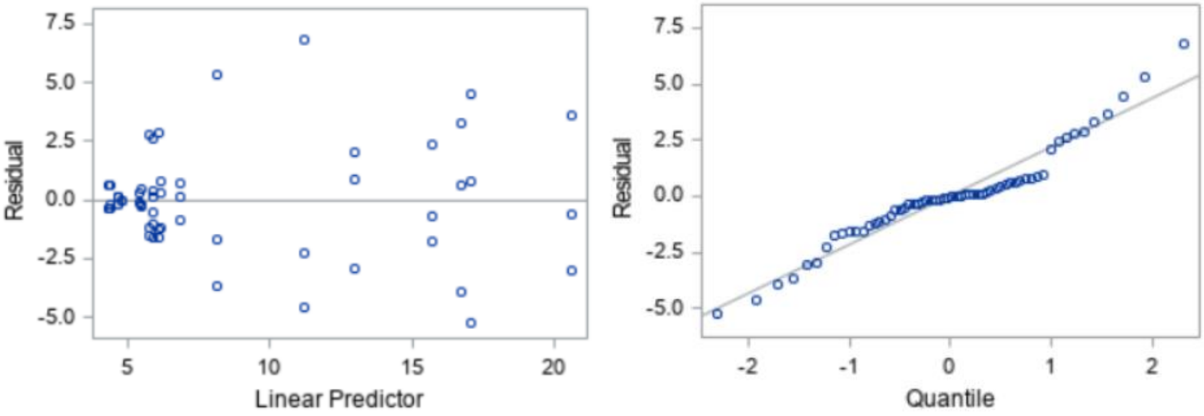

Figure S6: Diagnostic plots for the model with average normal load as response