ABSTRACT

HEAGY, KIM. Cultural Management Practices for Maximizing and Predicting Pumpkin Yield. (Under the direction of Dr. Jonathan Schultheis, Dr. Melinda Knuth, Dr. Jason Ward).

Pumpkins grown in North Carolina are a nascent specialty crop, only rising to a national production level in the last ten years. With this recent development, there are only general cultural management guidelines for the state, creating a large variation in plant density and inefficient fruit production. Adding to this, harvested pumpkins are sorted based on approximate fruit size and packed into corresponding bin categories of *Medium*, *Large*, *Extra-Large*, and *Jumbo*. The fruit sizes are not standardized across the industry and sorting is completed on a subjective, visual basis. These bins are sold at a flat rate. Predicting fruit yield is important for any crop to effectively market the crop and prepare appropriately for harvest. For pumpkins, both fruit quantity and fruit size are required for predicting fruit size since the crop is sold in categorical bins based on size. To assist with predicting yield and other in-season crop information, growers are utilizing Unmanned Aerial Vehicles (UAVs) as well as object detection software models. These systems have increased in popularity as the technology becomes more affordable and easier to operate; however, the accuracy for detecting and measuring pumpkins has only been research in small sample sizes.

Studies were conducted to streamline pumpkin yield through evaluating plant density, standardizing bin categories, and assessing the accuracy of drone image yield prediction. Studies in plant density measured the cultivar ‘Kratos’ fruit size and fruit yield per area for densities of 2691, 3588, 5382, and 10764 plants per hectare. Results indicate that as plant density increases, fruit quantity and total fruit weight per hectare increases Inversely, as plant density increases, fruit size decreases in diameter, length, and weight. The impact of row width was evaluated at 1.5 and 3.0 m. Pumpkin plants produced more weight per hectare and larger individual pumpkins

at the 1.5 m versus the 3.0 m row width. Pumpkins from bins categories *Medium, Large, Extra-Large,* and *Jumbo* at a commercial pack house were measured for fruit size. Fruit between bins were different in diameter, length, and volume. From these observations, the suggested standard fruit diameter for each category is *Medium:* 23.5 – 26.8 cm, *Large*: 26.9 – 29.9 cm, *Extra-Large*: 30 – 33.6 cm, and *Jumbo*: 33.7 – 35.5 cm. The plant spacing data and the bin category data were synchronized to predict the bin category and quantity for each plant density based on the density's expected fruit quantity and fruit size. Additionally, a partial budget was completed to show the financial implications of plant density through input costs and bin profits. The highest profiting density is 10764 plants per hectare earning $36,890 with 305 bins of *Extra-Large* pumpkins. UAV images from the production study were used to evaluate the detection model Solvi, an online software which processes and analyzes UAV images. The model was assessed for both detecting pumpkins and measuring fruit diameter. Detection was highly accurate for mature pumpkins with an overall accuracy of 99% and an overall error rate of 1%. Measuring fruit had more variation between methods with the detection model overestimating the mean diameter by 1.1 cm.

These results provide resources for pumpkin growers to optimize yield and increase profit through efficient plant density and targeted fruit size production for specific bin categories. Additionally, growers can predict yield and prepare for harvest by using commercially available UAVs and object detection models.

Cultural Management Practices for Maximizing and Predicting Pumpkin Yield.

by
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APPROVED BY:

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DEDICATION

I dedicate my thesis to my dad, Nelson Heagy. Thank you for forgoing the family business of dairy farming and planting a peach orchard instead.

BIOGRAPHY

I was born in Lebanon county and spent the first 18 years of my life in this area among the dairy farms and Mennonite communities. A decade before I was born, my parents started a peach orchard which shaped most of my childhood and our family dynamics. I am the youngest of four sisters. We spent our summers out in the orchard picking cherries from the loader bucket, hauling peaches to local roadside markets, and swapping stories about the Pick Your Own customers. It is difficult to tease apart my family and the orchard from one another. In a way, the orchard has always been the seventh family member.

Agriculture was so common in my hometown that I couldn't bring myself to study it after high school. I majored in Food Science at Penn State and I thoroughly enjoyed my studies well as eating ice cream during food chemistry lab. Food is the most significant common thread among humans. I was drawn to it and wanted my career to sit at the overlap of food and people.

After school I worked for Mars as a product developer on coffee and tea products. My favorite part of this job was taking an idea, creatively developing a rough prototype, and then slowly reforming it into a finished, complete product. The people and the company made this job worth it, but after some years I found myself longing to be outside in the sunshine and working with my hands again.

The decision to go to graduate school was silently percolating for years and then loudly precipitated all at once. Graduate school was never in my life plan, but I feel very strongly that I was called to this as a next step. For horticulture, I am no longer left wondering, *will it wash out in the water, or is it always in the blood?*

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First, I would like to acknowledge my committee members. Thank you for providing guidance and direction in my research and writing. You each provided technical expertise in varying areas, giving me a dynamic research experience. I have asked many questions and you have answered them patiently and thoroughly.

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I also want to acknowledge my family. To my parents, Nelson and Joanne Heagy, the greatest gift is having the two of you as my cheerleaders. Thank you for knowing me better than I know myself, your Sunday evening calls, and digging through the newspaper bin to show me fruit magazine articles. To my sisters, Christy, Greta, and Kelly, the way you each have responded to challenges in your life has caused me to grow in my own response to hardships. Your tenacity, fierce protection, and humble perseverance has not gone unnoticed. To my family, we all live on a purple dinosaur.

Finally, the authors would like to thank the North Carolina Specialty Crop Block Grant and CucCAP: SCRI Grant for funding this research.

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CHAPTER 1

High Density Planting and a Smaller Row Width Increased Yield

and Decreased Fruit Size for Pumpkins

(In the format appropriate for submission to HortScience)

Abstract

Pumpkins grown in North Carolina are a nascent specialty crop, only rising to a national production level in the last ten years. There are only general cultural management guidelines for this region which creates variation in plant density and inefficient production. Production field studies were conducted on the cultivar 'Kratos' (*Cucurbita pepo*) to investigate the impact of plant density and row width on marketable yield and individual fruit size for large carving pumpkins. Plant densities of 2691, 3588, 5382, and 10764 plants per hectare with row widths of 1.5 and 3.0 m were grown in 2020 and 2021 in North Carolina. Data were collected on fruit size, fruit size variance, and yield per area. Fruit size in terms of weight, length, and diameter increased as plant density decreased. There was no difference in fruit size variation between plant densities and row widths. Fruit number per hectare and fruit weight per hectare increased as plant density increased with the highest production at 10764 plants per hectare. For years combined, reducing row width from 3.0 to 1.5 m increased fruit weight and diameter but not length. Additionally, the 1.5 m row width produced more fruit weight per hectare than the 3.0 m row width for both years. Growers can optimize fruit weight per area and fruit number per area by using a density of 10764 plants per hectare. Overall, using a row width distance that is more equidistant to the in-row spacing promotes higher fruit yield and larger fruit size.

Introduction

There is a growing demand for pumpkins (*Cucurbita sp.)* in the United States (U.S.) with an increase of ornamental use and seasonal agrotourism among consumers (USDA ERS 2015). Commercial production within the U.S. has climbed from 662.3 million kilogram (kg) in 2000 to 687.6 million kg in 2010 to 991.6 million kg mostly recently in 2021 (ESMIS USDA 2022). Pumpkins are primarily used for food processing and seasonal decoration which include

traditional carving pumpkins and specialty pumpkins. Interest in specialty pumpkins continues to grow among U.S. consumers (USDA ERS 2022).

Pumpkins are an emerging crop for North Carolina with the first national production records reported in 2016 (USDA NASS 2018). Pumpkins serve as a supplemental crop for commercial North Carolina growers where most plant between 0.4 to 2 hectares (ha) to provide additional income to their larger staple crops (NCDA&CS 2023). Most large acreage of pumpkins are grown in the western mountain region which has a cooler plant zone (6a) compared to the rest of the state. In 2021, North Carolina produced 13.3 million kg of pumpkins over 1,498 ha of land. Pumpkin production has fluctuated from 8.0 million to 42.5 million kg since 2016 (USDA NASS 2022).

Pumpkins can be grown throughout the U.S. However, management practices differ based on the myriad of growing regions (USDA ERS 2022). These management practices, such as plant density, must be developed for each individual growing region. Plant density and plant spacing are two terms to articulate the same attribute. Plant density is specifying the plant quantity in the context of plants per hectare, while plant spacing specifies the area each plant occupies. The plant spacing recommendation for the Southeast region of the U.S. ranges from 1.7 m^2 to 2.8 m^2 for semi-vine growth habit pumpkins, the equivalent of 5883 and 3571 plants · ha^{-1} respectively (Kemble et al. 2022). North Carolina does not have state specific plant spacing recommendations for commercial pumpkins. If there were clear guidelines, growers could potentially grow pumpkins more efficiently. On average, North Carolina has lower yield per area compared to other states (USDA NASS 2022). North Carolina produced 8,850 kg·ha^{-1}, compared to top producing Illinois at 45,932 kg·$ha^{-1}$and other states like New York and Virginia which yielded 16,805 and 19,494 kg·ha^{-1} respectively (USDA NASS 2022). Establishing plant spacing

guidelines could increase yield per area for the North Carolina growing region. Although plant spacing guidelines can help improve production, there are many other factors such as plant growth habit, soil type, environmental conditions during the production season, and pests that impact pumpkin production.

Plant density is an effective management tool to influence fruit yield. There is an ideal plant density for every crop where competition for environmental resources is minimized and plant yield is maximized (Holliday 1960). Fruit yield will continue to increase at higher plant densities until the carrying capacity is met, resulting in a final constant yield (Weiner 1990). Cucurbits grown at a high plant density will lead to higher fruit number per area (Wehner et al. 2020). In a New York study, a vine-type growth habit pumpkin, 'Howden,' and semi-vine growth habit pumpkin, 'Wizard,' increased in fruit number and total weight per hectare by increasing density from 2290 to 8690 plants $\cdot ha^{-1}$ (Reiners and Riggs 1999). A study in Egypt also had increased fruit total weight per hectare with vine-type 'Dickinson' by increasing density from 4780 to 9560 plants $\cdot$ ha^{-1} (El-Sayed et al. 2011). Another study in northern Mississippi tested plant density to establish a recommendation for their region using semi-vine 'Aspen' and vine-type 'Howden Biggie' (Cushman et al. 2004). 'Aspen' had the highest fruit number and total weight per hectare with a density of 5051 plants $\cdot$ ha^{-1}, but yields decreased when plant density increased to 7577. 'Howden Biggie' deceased in fruit per hectare and significantly decreased in total weight per hectare as density increased. This is not consistent with other studies which reported an increase of fruit number and total weight as plant density increases. The authors of the Cushman study attribute this contrary outcome from testing densities that were too low to see the beneficial impact of higher plant densities.

Plant density also impacts the individual fruit size with a higher density producing a smaller fruit. Average fruit weight decreased for both ‘Howden’ and ‘Wizard’ when plant density increased from 2990 to 8960 plants · ha^{-1} (Reiners and Riggs 1999). For these varieties, the average fruit weight reduced from 9.6 to 8.9 kg at one study location and 9.4 to 7.4 kg at a second study location. The vine-type ‘Dickinson’ also decreased from 3.4 to 2.9 kg in average fruit weight when plant area changed from 4780 to 9560 plants · ha^{-1} (El-Sayed et al. 2011). Again, an increase in plant density significantly decreased the average fruit weight for ‘Aspen’ and ‘Howden Biggie’ (Cushman et al. 2004).

In addition to fruit size, fruit size variation is an important factor when growing a horticultural crop. Many horticultural crops are voluntarily graded and sold based on standards set by the government or industry corporations (Kader 2002). If there is a high variability in fruit size, more fruit will fall below or above the standardized size creating product waste, inefficiency in harvesting, or a reduction in crop price. Commercially, pumpkins are sold in bulk bins based on fruit size which means that uniform fruit would streamline fruit packing. Currently it is not known how plant density impacts fruit size uniformity for pumpkins. This is a current gap in the literature which this study aims to fill.

Plant density is controlled on a plant area basis with row width (the space between rows) and in-row spacing (the space between plants within a row). In practice, the row width distance is typically wider than in-row distance to accommodate field equipment for crop maintenance. The shape of the plant area, dictated by the relationship of row width and in-row measurements, affects the crop yield. When the spacing dimensions are equidistant, crops have a higher yield since a square shape compared to a rectangular shape reduces plant to plant competition (Pant 1979). Row width recommendations pumpkins for the Southeast region is 1.8 to 2.4 m while in-

row spacing recommendation is 0.6 to 1.2 m (Kemble et al. 2022). Previous pumpkin studies have compared in-row spacing while keeping the row width at a fixed distance. Studied row widths have varied from 1.8 to 2.4 m, assessing plant areas from 0.5 to 6.7 m^2 (Reiners and Riggs 1997, Cushman et al. 2004, El-Sayed et al. 2011). There is one previous pumpkin study that specifically looked at reducing row width while maintaining the same plant density. This study had three plant areas 1.1, 2.2, and 3.2 m^2, equivalent to plant densities of 2290, 4480, and 8960 plants · ha^{-1} at two different row widths, 1.8 and 3.6 m. The reduction in row widths led to higher fruit per hectare and smaller fruit size within each plant density (Reiners and Riggs 1999). With only three plant densities formerly studied, there is a gap in the literature for the impact of row width on pumpkin production.

The objective of this research was to investigate the impact of plant density and row width spacing on fruit size, fruit number per hectare, and total fruit weight per hectare for semi-vine pumpkins in North Carolina. Additionally, this research explored the effect of plant density and row width spacing on fruit size uniformity. The goal of the research was to provide plant density guidelines for commercial pumpkin production in North Carolina.

Materials and Methods

This research was conducted in Laurel Springs, North Carolina (lat. 36.398789°N, long.81.307266W°) at the North Carolina Department of Agriculture & Consumer Services Upper Mountain Research Station. The field site had a soil type of Toxaway loamy (USDA NRCS 2022) and was sown in the previous fall with an annual rye cover crop. A burndown herbicide (Appendix A) was utilized to kill the cover crop in the spring. A two week period was allowed before applying pre-plant fertilizer, discing, and rototilling the field. Two pre-plant fertilizers were applied, 112 kg·ha^{-1} of 0N–0P–50K and 329.3 kg·ha^{-1} of 17N–17P–17K. Thirty-

five days after planting, plots were side-dressed with 39.2 kg·ha^{-1}of 15N–15P–15K. ‘Kratos’ (*Cucurbita pepo*) (HM. Clause, Davis, California) is characterized by the company’s cultivar description as a 9-13 kg large carving pumpkin with a semi-vine growth pattern. It was chosen for this study since it is the most popular cultivar for U.S. growers (Froese J, personal communication). Four plant densities were tested, 10764, 5382, 3588, and 2691 plants · ha^{-1}, which are equivalent to plant areas of 0.9, 1.9, 2.8, and 3.7 m^2 respectively (Table 1.1). Each of the plant densities were tested at two different row widths, 3.0 and 1.5 m, with in-row measurements adjusted to meet the specified plant density. The 3.0 m row width had in-row spacings of 0.3, 0.6, 0.9, and 1.2 m, while the 1.5 m row width had in-row spacings of 0.6, 1.2, 1.8, and 2.4 m. The eight-treatment study was set up in a randomized complete block design with 3 replications in 2020 and 4 replications in 2021. Each plot had four rows measuring 12.2 m in length.

Seeds were planted using a crow hop similar to “Easy-Plant Jab Type” planter (Johnny’s Selected Seeds, Winslow, Maine) which presses seeds into the ground and lightly covers them. Sowing was 5 June 2020 and 17 June 2021. Two seeds were planted per hill and thinned to one after plants were established. Fifty-four of the plots had a 90% or greater plant stand. The remaining two plots had 80% and 85% plant stand. Plants were scouted regularly. Insecticides, if necessary, were selected based on positive identification of pests that had reached economic threshold levels. A disease management program (Appendix A) was implemented just prior to blooming with protectant sprays that continued every 7 to 14 days until harvest based on rainfall between sprayings. The primary diseases of concern were *plectosporium*, cucurbit powdery mildew (*Pseudoperonospora cubensis*), and cucurbit downy mildew (*Podosphaera xanthii* and *Erysiphe cichoracearum*). Once detected through scouting, the disease spray program would

incorporate more advanced curative chemistries. Modes of Action were rotated to reduce risk of resistance development. Weeds were well maintained through the spray program which ensured any competition effect was attributed to plant-to-plant spacing. No supplemental irrigation was used.

A one-time harvest was on 1 October 2020 and 23 September 2021, which totaled a 98-day growing period each year. The harvest area was 25% of the four row plots, which contained the middle sections of the inner two rows. This centrality was used to ensure a consistent plant-to-plant competition effect. The harvest area for the 3.0 m row width spacings measured 6.1 by 6.1 m, a total area of 37.2 m^2. The harvest area for the 1.5 m row width spacings measured 6.1 by 3.0 m, a total area of 18.6 m^2. Data were collected on marketable pumpkins for weight, diameter, length, and fruit number per plot. Length was the distance between the stem to blossom end of the fruit and diameter was the largest distance across the fruit perpendicular to length. Marketable pumpkins included mature orange fruit and green pumpkins that would color to orange off the vine. Rotten, immature, or severely blemished fruit were not included.

In 2020 the average daily high was 24.0 °C and average low was 14.5 °C with 50.0 cm of total precipitation during the growing season (Figure 1.1) (NCARS 2022). In 2021 the average high and low were 24.7 and 14.1 °C, respectively, with 44.1 cm of total precipitation. Weather information was collected by an onsite weather station at the Upper Mountain Research Station.

Analysis of variance was completed to test the significance of plant density and row width on yield components. A linear regression analysis was used to quantify how much these variables predict each other. Statistical analysis was completed using SAS 9.4 GLM and Mixed Procedures (SAS Institute, Cary, North Carolina). Raw data were transformed to include yield per hectare measurements.

Results and Discussion

There was a year by treatment interaction for fruit number per hectare ($p<0.001$) and fruit weight per hectare ($p<0.001$), therefore these variables were analyzed as separate years. This interaction was evident when scaling the data from a 37.2 and 18.6 m^2 plot area to a hectare. There was no year by treatment interaction for fruit weight ($p=0.0897$) diameter ($p=0.452$), length ($p=0.901$), and fruit uniformity ($p=0.301$), therefore these variables were analyzed as combined year data sets.

Fruit Weight

Fruit weight linearly decreased as plant density increased (Figure 1.2A). A density of 2691 plants · ha^{-1} had a mean fruit weight of 12.0 kg compared to a density of 10764 plants · ha^{-1} which had a mean fruit weight of 7.9 kg (Table 1.2). Plant densities had different fruit weight except for 3588 and 2691 plants · ha^{-1} which were not different. The reduction in fruit weight aligns with previous pumpkin studies where fruit weight decreased for different growth habit varieties when plant density increased (Reiners and Riggs 1997, El Sayed 2011). This was also true for watermelon studies which reported a decrease in fruit weight with decreased plant area and in-row spacing (Brinen et al.1979, Sanders et al. 1999).

There was an effect of the row width on fruit weight ($p=0.027$) (Table 1.2). The mean fruit weight for 1.5 m row width was 10.5 kg compared to the 3.0 m row width fruit weight of 9.9 kg. The 1.5 m row width may have produced larger fruit due to the more equidistant growing area compared to its 3.0 m row width counterpart. Square plant spacing patterns reduce the plant-to-plant competition and allow a higher yield than rectangular plant spacing patterns (Pant 1979). The results underline that it is possible to grow larger fruit at the same plant density through using a smaller row width, creating a more equidistant planting area. Our results are contrary to

another row width study where decreasing the row width spacing from 3.6 to 1.8 m had negligible effect on fruit size for plant densities of 2290, 4480, and 9860 plants · ha^{-1} (Reiners and Riggs 1999). Reiners and Riggs stated that the impact of row width spacing may become significant at higher plant densities.

Fruit Diameter & Length

Fruit diameter linearly decreased as plant density increased (Figure 1.2B). Increasing the plant density from 2691 to 10764 plants · ha^{-1} decreased the fruit diameter from 34.9 to 29.4 cm (Table 1.2). Plant densities produced different fruit diameters except for 2691 and 3588 which were not different from one another. The row width had an effect on the fruit diameter ($p=0.022$) (Table 1.2). The row width of 1.5 m had a fruit diameter of 33.1 cm compared to 3.0 m which had a diameter of 32.2 cm.

Fruit length linearly decreased as plant density increased (Figure 1.2C). The density of 2691 plants · ha^{-1} had a fruit length of 31.6 cm compared to the density 10764 plants · ha^{-1} which had a fruit length of 27.4 cm (Table 1.3). Similar to fruit weight and diameter, the plant densities of 2691 and 3588 were not different from one another in fruit length. The row width did not have an effect on fruit length ($p=0.097$).

Many studies report that fruit size decreased with increased plant density; however, the exact relationship between diameter and length were previously unknown. In literature reviewed for this research, fruit size was reported by fruit weight or volume, but not individually by fruit diameter or length. Cushman et al. (2004) reported a reduction in fruit volume for 'Aspen' as plant density increased from 5051 to 7577 plants · ha^{-1}. Mathematically, since volume is based on length and diameter, our results of decreased length and diameter are similar to Cushman's results with decreased fruit volume. Our study clarifies how the individual metrics of diameter

and length change with the reduction of overall fruit size. From our results, diameter and weight are correlated at R^2=0.90 and length and weight are correlated at R^2=0.77, revealing that diameter is a better indicator for overall fruit size than length. A limitation of this study is that these correlations are specific to the 'Kratos' cultivar. The relationship between fruit diameter and length may differ for other cultivars.

In summary, these results show that 'Kratos' pumpkins decrease in fruit weight, length, and diameter with increased plant density. Plant densities of 2691 and 3588 are not different from one another in fruit weight, diameter, or length. This indicates that decreasing the plant density below 3588 will not yield larger pumpkins. Within each plant density, a 1.5 m row width will yield larger pumpkins compared to 3.0 m row width for weight and diameter, but not for length. Growers can maximize fruit size while minimizing land by using a density of 3588 plants $\cdot$ ha^{-1} with a 1.5 m row width.

Fruit Uniformity

The uniformity in fruit size was not different across plant densities and row widths for both years (p=0.233). Growing a consistently sized fruit benefits growers since pumpkins are packed and sold commercially in bulk bins based on fruit size. Less variance in fruit size streamlines the sorting and packing process for growers. Since plant densities and row widths were not different, growers do not need to consider fruit uniformity while choosing the appropriate plant density for their production. There were no previous studies to compare against since fruit size uniformity based on plant density has not been previously reported. A limitation of this study is that 'Kratos' was the only pumpkin evaluated. Other pumpkin cultivars may vary in fruit size uniformity at different plant densities.

Fruit Yield: Fruit number per hectare

Fruit number per hectare linearly increased as plant density increased in both 2020 and 2021 (Figure 1.3A, B). In 2020, fruit number per hectare increased from 4,081 to 12,648 fruit · ha^{-1} as plant density increased from 2691 to 10764 (Table 1.3). Similarly, 2021 had an increase from 4,676 to 9,149 fruit · ha^{-1} with the same density increase. By increasing the plant density, the fruit number per hectare increased 209% in 2020 and 95% in 2021. The difference in fruit quantity was observed at a plot basis (Figure 1.4). For both years, plant densities of 2691 and 3588 were not different for fruit number per hectare. Additionally, 10764 plants · ha^{-1} produced more fruit per hectare than all other densities for both years. The increased fruit quantity follows the results of many other studies. Reiners and Riggs (1997, 1999) had two different studies where pumpkin quantity per hectare increased with increased plant density. Watermelon studies show similar results where fruit quantities increased with higher plant density until an upper threshold limit was met (Sanders et al. 1999).

In 2020, row width had an effect on fruit quantity per hectare ($p<0.001$) (Table 1.3). The 1.5 m row width had 8,342 fruit · ha^{-1} compared to 6,144 for 3.0 m row width, a difference of 36%. The results from 2020 assert that at the same plant density, pumpkin quantities increase with more equidistant plant area. Inter-plant spacing is important since plants respond to neighborhood densities (Weiner 1990). These results align with a New York study which reported that at a high density of 8960 plants · ha^{-1}, a 1.8 m row width produced more fruit per hectare compared to a 3.6 m row width (Reiners and Riggs 1999). In 2021, row width spacing did not have an effect on fruit quantity per hectare ($p=0.352$); however, as in 2020, a trend of more fruit was produced in the 1.5 m than the 3.0 m row width (Table 1.3). The discrepancy of the effect row width on fruit yield between the two years is not fully understood. The growing

conditions for these years were both within normal regional ranges, eliminating the potential difference caused by temperature or rainfall accumulation.

Fruit Yield: Kilograms per hectare

Total fruit weight per hectare is an effective way to measure the overall productivity of a plant density. It simultaneously considers the decrease in fruit size against the increase in fruit number as plant density increases. Increasing plant density linearly increased fruit yield in kilograms per hectare for both years of the study (Figure 1.3C, D). In 2020, increasing density from 2691 to 10764 plants · ha^{-1} increased yield 98% from 48,227 to 95,365 kg · ha^{-1}(Table 1.3). In 2021, this same increase in plant density increased yield 30% from 56,223 to 73,261 kg · ha^{-1}. These results are aligned with previous pumpkin density studies in which fruit yields increase with increasing plant density (Reiner Riggs 1999, El Sayed 2011). This increase in yield occurs in other crops such as watermelon and squash (Brinet 1979, Dweikat 1989, Nesmith 1993). However, a pumpkin study showed the opposite effect, where fruit yield in kilograms per hectare decreases with increased density (Cushman et al. 2004). This result was attributed to testing lower plant densities where the benefit of smaller plant areas was not captured by the data.

The 1.5 m row width had higher fruit yield compared to the 3.0 m row widths in 2020 ($p<0.001$) and 2021 ($p=0.010$) (Table 1.3). In 2020, the 1.5 m row width yielded 79,783 kg · ha^{-1} compared to the 3.0 m row width with 54,692 kg · ha^{-1}. Similarly, in 2021, the 1.5 m row width yielded 68,241 kg · ha^{-1} compared to 58,849 kg · ha^{-1} from the 3.0 m row width. The outcome of this study communicates that total weight per hectare increases by decreasing the row width. The 1.5 m row width created a more equidistant growing area, allowing the plants to be more productive through fruit yield (Pant 1979). Comparable to our results, the Reiners and Riggs

(1999) study had higher fruit weight per hectare at a 1.8 m row width compared to a 3.6 m row width at a plant density of 8960 plants · ha^{-1}.

Conclusion

This research specifies the effect of plant density and row width on yield for the pumpkin cultivar 'Kratos' and provides plant spacing recommendations for growers. Our results validate that by increasing plant density pumpkin fruit size decreases, fruit number per area increases, and fruit weight per area increases. Fruit size increases with decreased plant density as low as 3588 plants ·ha^{-1}. Conversely, fruit weight and fruit number per area increase up to the highest density of 10764 plants · ha^{-1}. From our study, pumpkins yield the most fruit weight per hectare at 10764 plants · ha^{-1} with a 1.5 m row width. For total weight per hectare and fruit size, a more equidistant area, created by row width and in-row distances, produces a more prolific yielding pumpkin plant.

A limitation of the study is only using on cultivar. Future studies on other popular cultivars would provide insight on how plant density affects yield for pumpkins as a general crop. Another limitation of the study is not reaching the upper yield threshold based on plant density. To continue this research, higher plant densities could be tested to determine the upper plant density threshold for 'Kratos' pumpkin yield.

Growers should consider their markets and management practices to select a plant density that is appropriate for their goals. We recommend 10764 plants·ha^{-1} for high volume production and 3588 plant· ha^{-1} for large individual fruit size production. The row width distance should be minimized while recognizing the limitations of machinery for field management. Overall, high plant density and narrow row width are applicable management practices for North Carolina pumpkin growers to increase space efficacy and maximize fruit yield.

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Table 1.1. Summary of plant area, row width, and in-row spacing to corresponding plant density for pumpkin plants.

Row Width Spacing (m)	In Row Spacing (m)	Plant Area (m^2)	Plant Density (plants/ha)
3.0	0.3	0.9	10,764
3.0	0.6	1.9	5,382
3.0	0.9	2.8	3,588
3.0	1.2	3.7	2,691
1.5	0.6	0.9	10,764
1.5	1.2	1.9	5,382
1.5	1.8	2.8	3,588
1.5	2.4	3.7	2,691

Table 1.2. Analysis of variance for pumpkin fruit weight, diameter, and length, for row widths and plant densities analyzed as combined years.

Treatment	Weight (kg)	Diameter (cm)	Length (cm)
Row Width (m)			
1.5	10.5 a [y]	33.1 a	30.0 a
3.0	9.9 b	32.2 b	29.6 a
Significance	0.027	0.022	0.097
Tukey's HSD [x]	0.5	0.7	0.5
Density (plants/ha)			
2,691	12.0 a	34.9 a	31.6 a
3,588	11.1 a	34.1 a	30.7 a
5,382	9.7 b	32.3 b	29.4 b
10,764	7.9 c	29.4 c	27.4 c
Significance	<0.001	<0.001	<0.001
Linear			
Tukey's HSD	1.1	1.3	0.9
Row Width * Density			
Significance	0.299	0.124	0.106

[x] Tukey's Honestly Significant Difference values at the 0.05 level.
[y] Comparisons are made within each column for each variable.

Table 1.3. Analysis of variance for pumpkin fruit number per hectare and kilogram per hectare for plant densities and row widths analyzed as separate years.

Treatment	Year			
	2020		2021	
	No. fruit/ha	Yield ($kg \cdot ha^{-1}$)	No. fruit/ha	Yield ($kg \cdot ha^{-1}$)
Row Width (m)				
1.5	8,342 a[y]	79,783 a	6,694 a	68,241 a
3.0	6,144 b	54,692 b	6,290 a	58,849 b
Significance	<0.001	<0.001	0.352	0.010
Tukey's HSD [x]	919	6,721	881	6,850
Density (plants/ha)				
2,691	4,081 a	48,227 a	4,676 a	56,223 a
3,588	4,844 a	53,790 a	5,046 a	56,002 a
5,382	7,400 b	71,569 b	7,097 b	68,692 ab
10,764	12,648 c	95,365 c	9,149 c	73,261 b
Significance	<0.001	<0.001	<0.001	0.002
Linear				
Tukey's HSD	1761	12,880	1670	12,984
Row Width × Density				
Significance	0.496	0.269	0.079	0.299

[x] Tukey's Honestly Significant Difference values at the 0.05 level.
[y] Comparisons are made within each column for each variable.

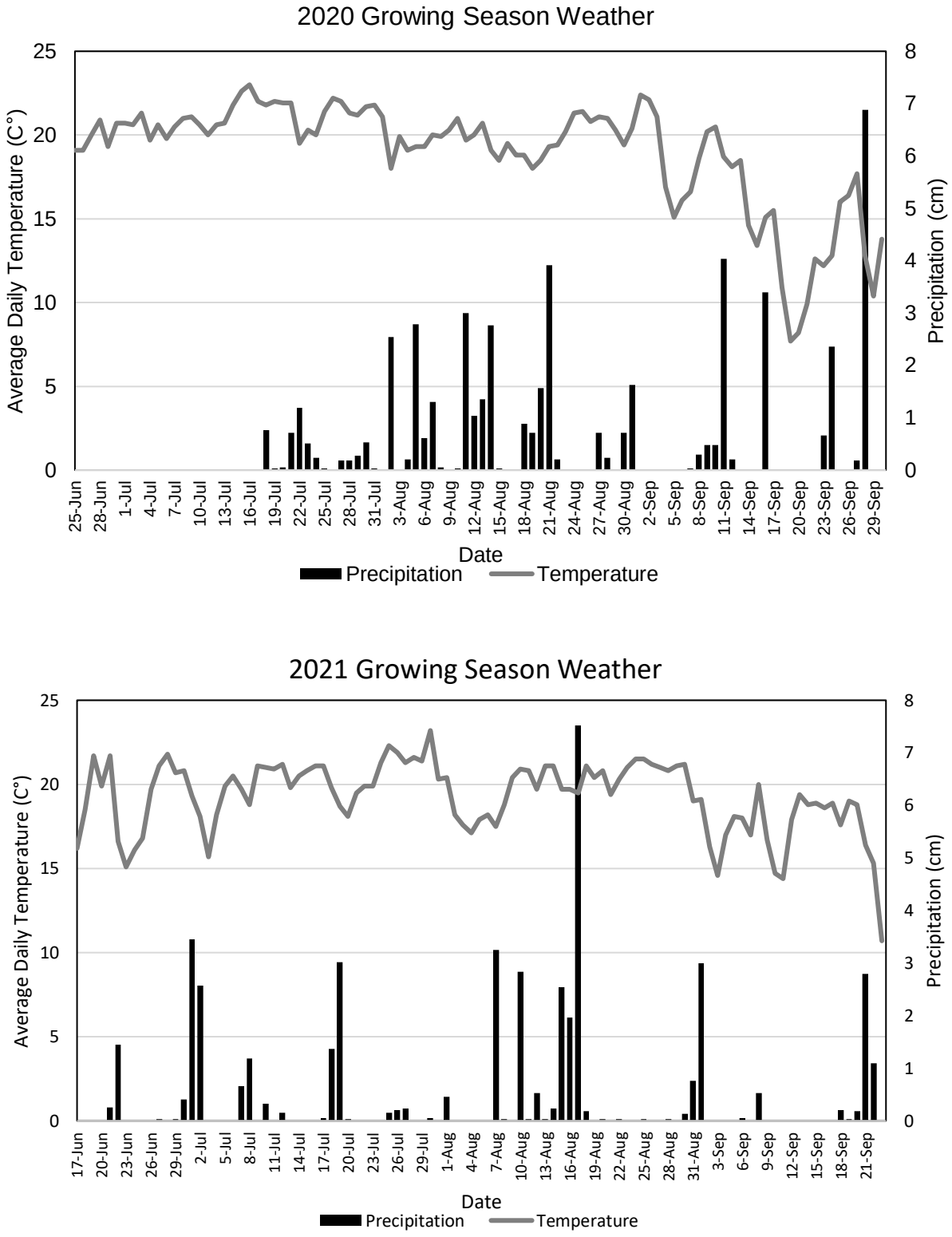

Figure 1.1. Growing season average daily temperature and total daily precipitation for Laurel Springs, North Carolina in 2020 and 2021.

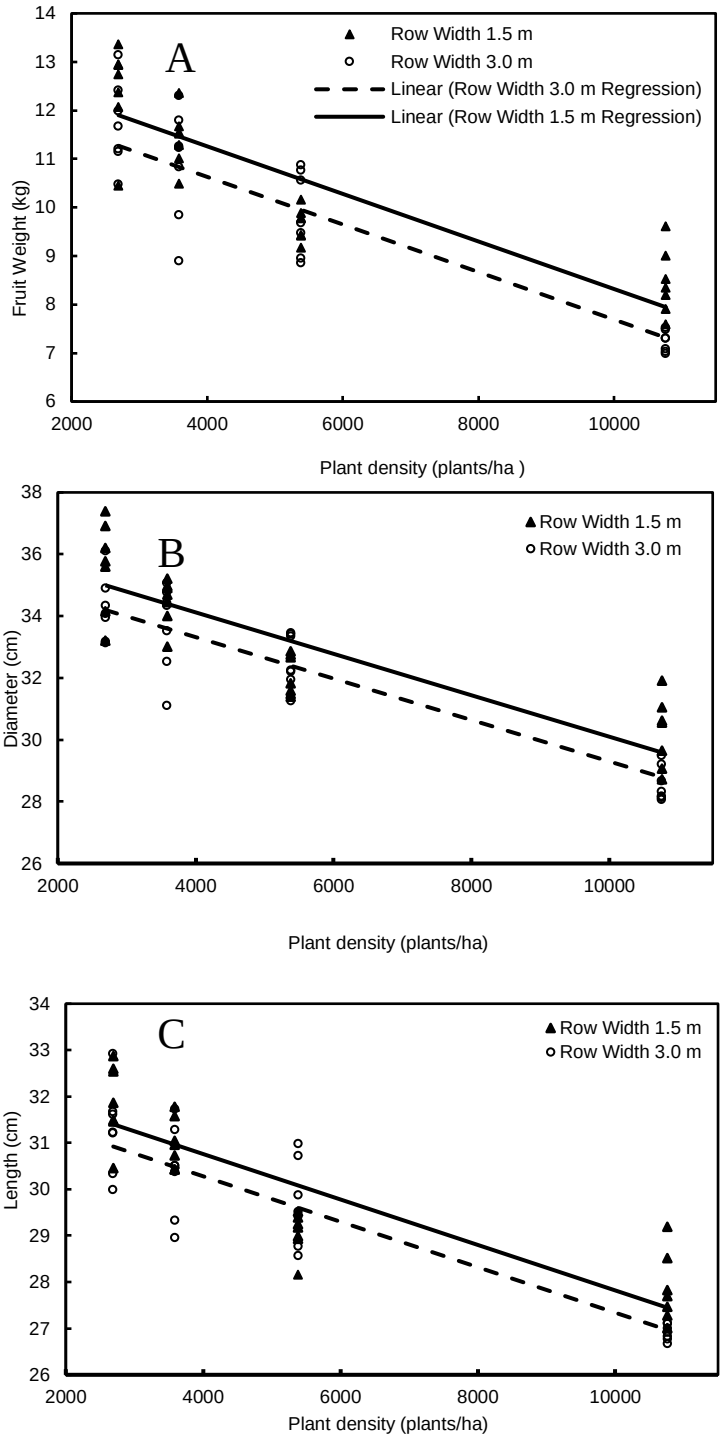

Figure 1.2. Fruit size yield components for 'Kratos' pumpkins grown at plant densities of 2691, 3588, 5382, and 10764 plants · ha^{-1} with row widths of 1.5 and 3.0 m. These components were analyzed as combined years with no year by population interaction. (A) R^2= 0.75, p value <0.001; 1.5 m row width: y = 13.22 + (-0.00049x); 3.0 m row width: y = 12.59 + (-0.00049x); (B) R^2= 0.79; p value <0.001; 1.5 m row width: y = 36.82 + (-0.00067x); 3.0 m row width: y = 36.0 + (-0.00067x); (C) R^2= 0.78, p value <0.001; 1.5 m row width: y= 32.72 + (-0.00049x); 3.0 m row width: y = 32.24 + (-0.00049x)

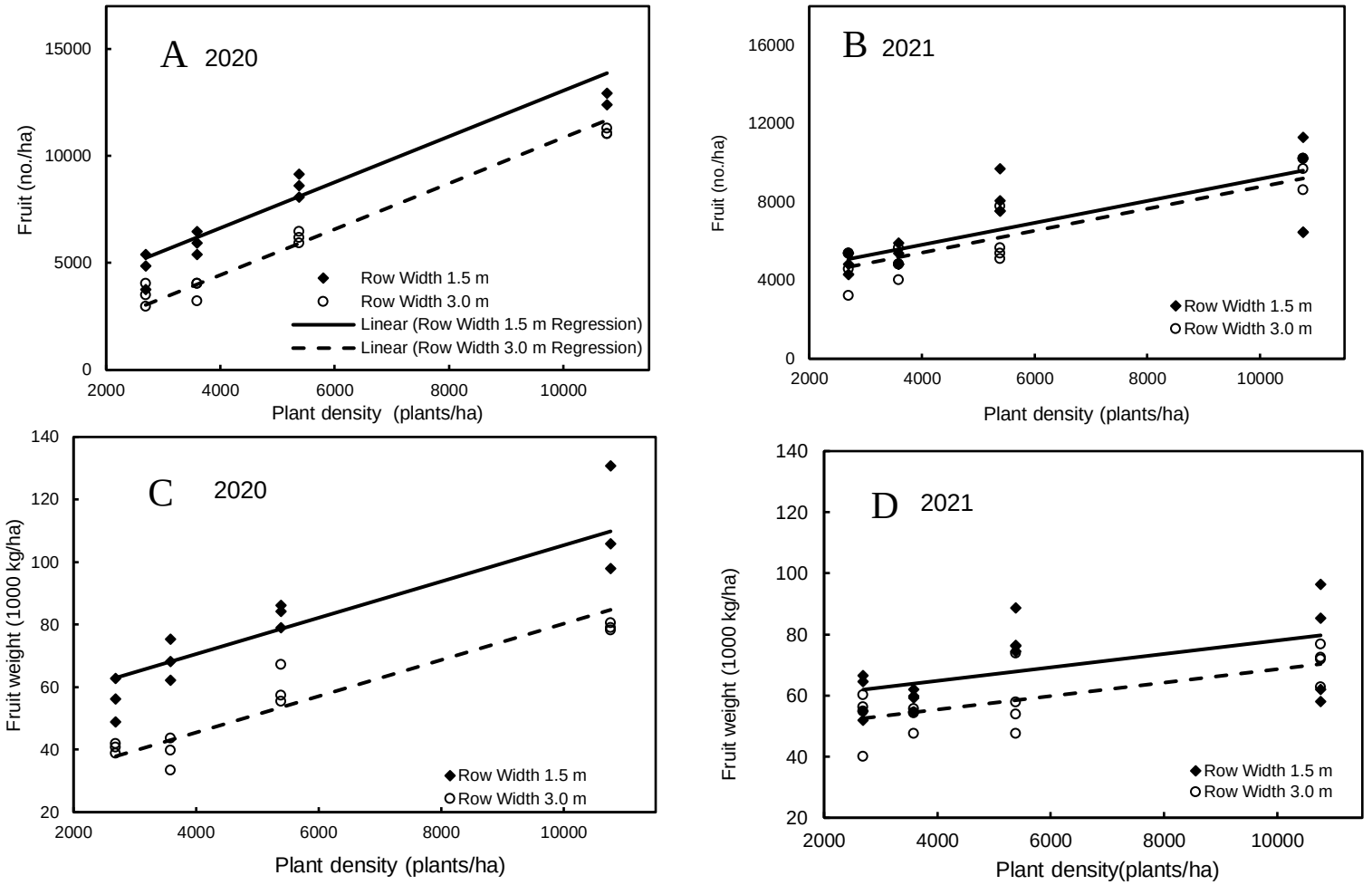

Figure 1.3. Per area yield components for 'Kratos' pumpkins grown at plant densities of 2691, 3588, 5382, and 10764 plants · ha^{-1} with row widths of 1.5 and 3.0 m. These components were analyzed per year with a year by population interaction.
(A) R^2= 0.85, p value <0.001; 1.5 m row width: y = 2353 + 1.1x; 3.0 m row width: y= 156 + 1.1x;
(B) R^2= 0.85, p value <0.001; 1.5 m row width: y=3580 + 0.6x; 3.0 m row width: y=3177+0.6x;
(C) R^2= 0.77, p value <0.001; 1.5 m row width: y = 47387 + 5.8x; 3.0 m row width: y = 22296 + 5.8x;
(D) R^2= 0.77, p value <0.001; 1.5 m row width: y = 56017 + 2.2x; 3.0 m row width: y = 46625 + 2.2x

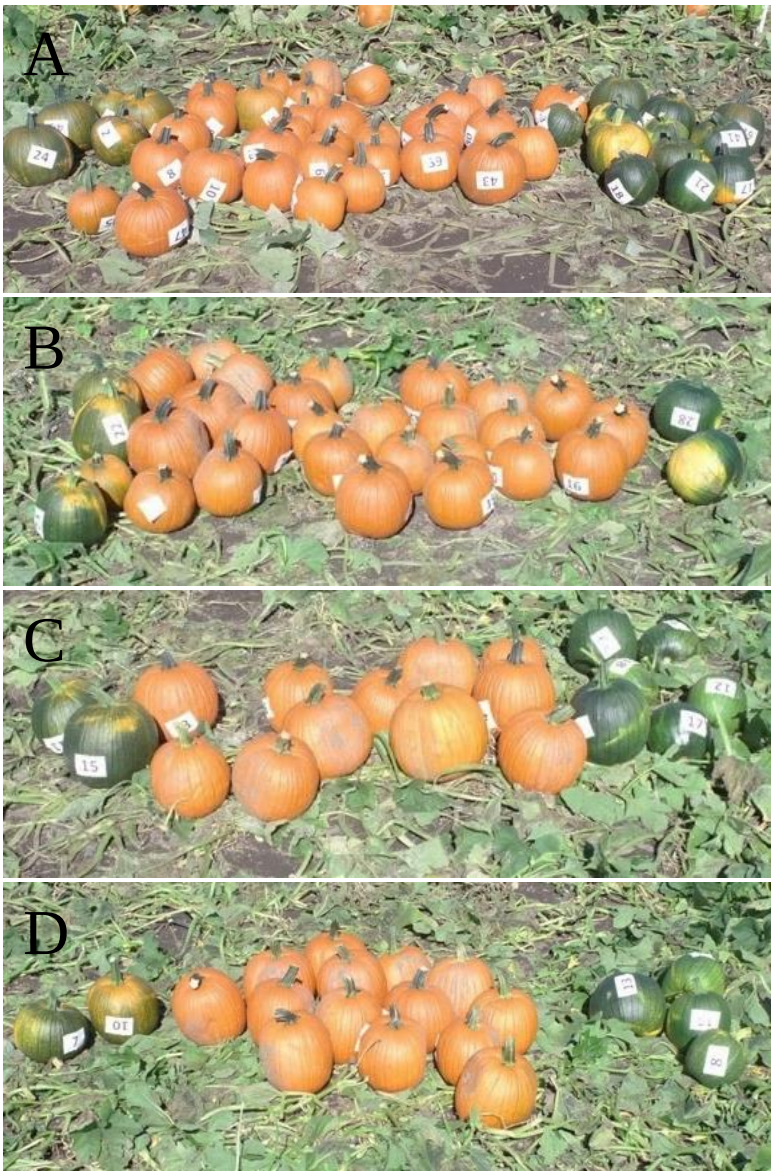

Figure 1.4. Pumpkin yields from 37.2 m^2 research plots at varying plant densities at with 3.0 m row width. (A) 10764 plants · ha^{-1} (B) 5382 plants · ha^{-1} (C) 3588 plants · ha^{-1} (D) 2691 plants · ha^{-1}

CHAPTER 2

Maximizing Profit of Commercial Pumpkin Production with

Bin Standardization and a Partial Budget Analysis

(In the format appropriate for submission to HortTechnology)

Abstract

Pumpkins are currently sold in commercial bins categorized based on fruit size. There are no standards for these fruit sizes which create discrepancy across the industry. Furthermore, there is not a published partial budget analysis for pumpkin fruit yield based on plant area. An observational study was conducted to quantify and standardize the fruit sizes of pumpkins packed into commercial bins. These proposed standardize fruit sizes were then correlated to expected fruit size and quantity of different plant areas to estimate the total commercial bin yield. Additionally, a partial budget analysis was conducted to calculate the greatest profit per hectare with the varying plant areas. Pumpkins from bins labeled *Medium*, *Large*, *Extra-Large*, and *Jumbo* were hand measured for diameter, length, and weight. Based on a discriminate analysis, 20% of pumpkins were incorrectly sorted based on current practices. A proposed standard fruit diameter for each bin size is *Medium*: 23.5 to 26.8 cm, *Large*: 26.9 to 29.9 cm, *Extra-Large*: 30.0 to 33.6 cm and *Jumbo*: 33.7 to 35.5 cm. The results of partial budget analysis show that the most profitable plant area is 0.9 m^2 which will earn \$36,890 $\cdot$ ha^{-1}. Profit for pumpkin production is contingent on both fruit quantity and fruit size as these factors dictate the quantity and category of commercial bins. Growers should consider both metrics to optimize their operation.

Introduction

The United States (U.S.) pumpkin (*Cucurbita sp.)* production has risen in the last 20 years with total production increasing from 662.3 million kilogram (kg) in 2000 to 687.6 million kg in 2010 and most recently 991.6 million kg in 2021 (ESMIS, USDA 2022). Among USDA surveyed states, including top producers Illinois, Indiana, California, Pennsylvania, and New York, the industry is valued at \$233 million with over 28,166 hectares (ha) harvested in 2021 (USDA NASS 2022). The top uses for pumpkins are Halloween jack o' lanterns, agritourism

activities in fall, and seasonal food products in autumn (USDA ERS 2015). These uses are rising in popularity, causing a growth in demand as seen from 2000 to 2014 with consumer usage rising 17% per capita (USDA ERS 2015).

North Carolina has recently entered the top pumpkin producing states, ranking sixth in 2019 (USDA NASS 2020). Most commercial growers in North Carolina harvest between 0.4 to 2 ha of pumpkins as a supplemental income to their large staple crops (NCDA&CS 2023). Larger quantities of pumpkins are grown in the North Carolina western mountain region of the state where the climate is cooler and the disease pressure is lower compared to the Piedmont and costal region in the east (Craddock, 2022). In 2021, the state harvested 13.3 million kg of pumpkins across 1,498 ha of land. The state had an average price of $0.56 per kg with the total value of utilized production at $7.3 million (USDA NAAS 2022).

Commercially, pumpkins are sold in standardized cardboard bulk bins. These bins are either 0.5 m or 0.9 m in height and fit on a standard pallet which measures 1.0 m by 1.1 m (Aegerter et al. 2013). Carving pumpkins are sorted based on size and are packed into bins with comparably sized fruit. This usually happens during harvest where pumpkins are sorted and packed in the field (Birdsell T, personal communication). The bins are subjectively sorted and labelled according to fruit size into categories of *Medium, Large, Extra-Large,* or *Jumbo* (ESMIS USDA 2022). Each fruit is marked with a sticker denoting its fruit size category. Bins are also labelled by the bin count, the projected number of pumpkins within a bin. Each bin count number is associated with a fruit size category. The bin size category with smaller fruit has a higher bin count while bin size with larger fruit has lower bin counts. Bin counts are a projection rather than an actual count and can create discrepancy between the bin count label and the actual number of pumpkins within the bin. Bin heights, 0.5 and 0.9 m, may vary based on preference and are not

directly associated with a specific fruit size or bin count. Bin prices do not change based on fruit size or bin count (ESMIS USDA 2022). Growers can receive the same price for a 55-bin count of *Medium* pumpkins and for a 20-bin count of *Jumbo* pumpkins.

The U.S. Department of Agriculture (USDA) Agricultural Marketing Services (AMS) create voluntary grades and standards for horticultural crops. Grade and standards establish a method to define and measure the value of a crop to create a common language for buyers and sellers (Spangler 1956, Kader 2002). Grades define the quality metrics of a commodity, while standards define other parameters such as commodity uniformity and packing requirements (Spangler 1956). There are grades and standards for over 80 horticultural crops (Kader 2002).

The U.S. pumpkin industry does not have size standards even though the fruit is sold primarily based on size. Other crops, such as watermelon, have specific size parameters and tolerances listed by the USDA AMS (2021). The last publication by the USDA regarding pumpkins was the *U.S. Standard for Fall and Winter Type Squash and Pumpkin,* published in 1983 which lists two grades but no size standards (USDA AMS 1983). Additionally, there are no industry resources which correlate pumpkin bin category to average fruit size for the North Carolina region (Birdsell T, personal communication). Without regulation and guidance, fruit sizes can vary within the same labeled bin category depending on the region, farm, or employee that sorted and packed the bin. Furthermore, pumpkins have a large fruit size range which introduces additional variation. For example, a seed company lists two cultivars, ‘Magician’ and ‘Howden Biggie’ as both producing ‘big’ pumpkins. The maximum predicted fruit weight for ‘Magician’ is 7.3 kg while ‘Howden Biggie’ is 22.7 kg (Harris Seeds, Rochester, New York). This wide range of fruit size between cultivars is amplified when fruit is subjectively categorized

and sold in bulk bins. Without standard sizes for pumpkins, there is no common language between buyers and sellers, creating a discrepancy in value.

The retail pumpkin season is in September and October, with wholesale pumpkin bin prices increasing closer to Halloween when the fruit is most demanded. In the 2021 season, the price for a bin of conventionally grown 'Howden' pumpkin started at $160 in early September and ended at $220 in the last two weeks of October, with the seasonal average being $190 across both bin heights (USDA ERS 2022). In the weeks leading up to Halloween, advertised retail price of a 'Howden' pumpkin peaked in the second week of September at $5.82 per pumpkin (USDA ERS 2022). Carving pumpkin prices fluctuate based on location and date, while pie and specialty pumpkins prices remain constant throughout the fall season. The top producing state Illinois grows food processing pumpkins which results in the lowest price at $0.08/kg (USDA NASS 2022). In 2021, Washington had the highest price at $0.82/kg. Prices in North Carolina have risen in the last few years rising from $0.16 to $0.41 to $0.55 per kg in the years 2019, 2020 and 2021 respectively (USDA NASS 2022).

Many studies have shown that decreasing plant growing area decreases fruit size. This was seen for both vine-type 'Howden' and semi-bush type 'Wizard' cultivars which decreased in fruit size as plant area was reduced (Reiners and Riggs 1997). In another study, fruit size decreased for vine-type 'Dickinson' but did not for bush-type 'Frosty' as plant spacing decreased (El Sayed et al. 2011). The conflicting results for 'Frosty' was attributed to the impact of genotype in growth habits between vine-type and bush-type The trend of decreasing fruit size can be seen in other cucurbits such as watermelon, where decreasing in-row spacing decreased the fruit weight (Brinen et al. 1979, Sanders et al. 1999). These studies show that plant spacing is a contributing factor for fruit size.

In addition to impacting individual fruit size, plant spacing also impacts overall yield (Weiner 1990). High density spacing, which is equivalent to smaller plant growing area, maximize yields in vegetable crops (Maynard and Hochmuth 2007). Crop yield will increase with increased plant density until the carrying capacity is met and a final constant yield is achieved (Weiner 1990). Several pumpkin studies have resulted in increased total fruit weight and fruit number per hectare when decreasing plant growing areas for multiple pumpkin genotypes (Reiners and Riggs1999, El-Sayed et al. 2011). This is seen in other crops where total yield increased for squash and watermelon with decreased plant growing area (Dweikat 1989, NeSmith 1993).

Even though there have been studies investigating the effect of plant spacing on fruit size and fruit yield, there are no resources which translate this yield into predicted commercial bins. Growers could accurately predict yield and prepare for harvest if they understood the expected bin category and quantity based on their management practices. Furthermore, growers can optimize production by leveraging plant spacing and bin size categories to find the highest yielding combination. This can be done by utilizing a plant growing area that grows the most pumpkins per hectare at the correct fruit size which returns the highest number of bins. Creating a resource of bin production based on plant growing area would enable growers to make informed management decisions resulting in a higher profit.

A partial budget analysis can be completed to measure the financial implications of adjusting plant spacing to target specific bin categories and maximize profits. A partial budget analysis is an economic tool which systematically evaluates the costs and benefits of changing a specific practice or technology within a current business operation (Cornelisse 2023). Increasing plant density would increase yield, but it would also increase seed costs, labor cost, and harvest

workload. A partial budget analysis would calculate if higher yield from a higher plant density would still be profitable with the additional input costs. Currently, partial budget analyses exist for other pumpkin management practices such as organic practices (Brumfield et al. 2000), biodegradable mulches (Galinato et al. 2020), and no-till (Penn State Extension 2014) but none exist for plant spacing and bin yield. By calculating a partial budget analysis on plant spacing, we could measure the profit of planting pumpkins at various densities in North Carolina.

The research objective of this study is to establish a standard fruit size for the commercial pumpkin bin categories *Medium*, *Large*, *Extra-Large*, and *Jumbo*. We hypothesize that current sorting practices are not consistent, and fruits of varying sizes are categorized in the same bin. Additionally, we wanted to correlate plant spacing to the estimated bin category and quantity. We hypothesize that a smaller plant area will have a greater profit than larger plant area because smaller plant area increases fruit yield per area and will result in a higher commercial bin yield.

Materials and Methods

Research for this paper was completed in three steps: a production study which measured plant spacing effect on fruit size, a commercial bin study which measured fruit size in commercial bins, and analysis of costs and profit from different planting size areas.

Production Information

The study plot was located at Laurel Springs, North Carolina, at the Upper Mountain North Carolina Cooperative Extension Research Station. The study assessed fruit yield for four plant growing areas, 0.9, 1.9, 2.8, and 3.7 m^2, which is equivalent to 10764, 5382, 3588, and 2691 plants $\cdot$ ha^{-1}. Each plant spacing was assessed at two row widths, 3.0 and 1.5 m, with the in-row spacing adjusted to meet the specified plant growing area. The 3.0 m row width spacing had in-row measurements of 0.3, 0.6, 0.9 and 1.2 m. The 1.5 m row width spacing had in-row

measurements of 0.6, 1.2, 1.8 and 2.4 m. The field was set up in randomized complete block with three repetitions in 2020 and four repetitions in 2021. Fertilizer was applied pre-plant, 112 kg·ha^{-1} of 0N–0P–50K and 329.3 kg·ha^{-1} of 17N–17P–17K, and a side dress of 39.2 kg·ha^{-1}of 15N–15P–15K thirty-five days after planting. North Carolina State Cooperative Extension employees at Upper Mountain Crop Research Station managed weeds and diseases through applying pesticides and hand weeding. No supplemental irrigation was used. There was a one-time harvest on 1 October 2020 and 23 September 2021 where 1,033 pumpkins were harvested over both years. Mature, blemished-free fruit were measured for weight, length (stem to blossom end) and diameter (the largest distance across the fruit perpendicular to length). The average daily high and low temperature during the 2020 growing season was 24.0 °C and 14.5 °C (NCARS 2022). In 2021, these metrics were 24.7 °C and 14.1 °C. Total rain accumulation was 50.0 cm in 2020 and 44.1 cm in 2021.

The production statistics of this study has been reported separately. Additional details on the location, field preparation, harvest, and data collection can be found here: REFERENCE.

Commercial Bin Information

This was an observational study conducted in 2022 in Jefferson, North Carolina. Pumpkins were provided by commercial producer Sexton Farms located in a 6a plant hardiness zone on a Watauga loam soil (lat. 36.406673°N, long. 81.424202°W) (https://sextonfarm.com, Jefferson, North Carolina) (USDA NRCS 2022). Sexton Farm planted their crop between the dates of 23 May and 1 June and mature pumpkins were harvested the first and second weeks of September. The observational study was completed at the Shatley Farms packing facility (lat. 36.439681°N, 81.430202°W) where pumpkin bins were being stored (https://www.shatleyfarms.com, Jefferson, North Carolina). Pumpkins were packed by Sexton

Farm employees into standard 0.9 m cardboards bulk bins and sorted into size categories of *Medium*, *Large*, *Extra-Large,* and *Jumbo* with the corresponding bin counts of 55-65, 40, 30, and 20 fruit per bin. Fruit was sorted by size based on employees' independent, subjective judgment. This is the standard for the industry (Birdsell T, personal communication). Cultivars included, but were not limited to, 'Hermes,' 'Racer Plus,' 'Kratos,' and 'Sweet Baby Jane' which were mixed within bins based on fruit size. Fruit from completed, filled commercial bins were taken out of the packed bins and were hand measured for length and diameter using a Haglof Mantax Aluminum caliper (https://haglofsweden.com, Madison, Mississippi). Three bins of each category were measured and recorded. There were 180 *Medium*, 118 *Large*, 90 *Extra-Large*, and 64 *Jumbo* pumpkins measured. A summary of the treatments from the production and commercial bin study are presented in Table 2.1. For simplicity in explaining the treatments, plant area sizes have been numbered 1-8 and the bin sizes have been numbered 9-12.

Pumpkin volumes were calculated based on the ellipsoid equation for volume $V = \frac{4}{3}\pi\, a\, b\, c$ where a, b, and c are each a radius on the planes *x*, *y*, and *z* measuring from the surface to the center of the ellipsoid. The diameter measurement was used for the radii *a* and *b* while the length measurement was used for the radii *c*.

For the production analysis, the independent variable was plant spacing and the dependent variables were fruit weight, length and diameter. For the commercial bin study, the independent variables were fruit weight, length and diameter, and the dependent variable was the resulting assigned bin category. Statistics were completed using SAS 9.4 (SAS, Cary, North Carolina) for Analysis of Variance and Discrimination tests with significance at a 0.05% level.

Partial Budget Analysis

The template for the partial budget analysis was taken from *Penn State Extension Agricultural Alternatives: Sample Watermelon Budget* (Penn State Extension 2014) and *Watermelon Production Enterprise Budget* (McMinn et al. 2017). Cost for seeds, chemicals, and soil amendments were the prices from suppliers of the Upper Mountain Research Station. These include Harris Seeds (Rochester, New York) and Nutrient Ag Solutions (Saskatoon, Canada). Labor cost for North Carolina in 2023 was $14.91 per hour which is set by the Adverse Effective Wage Rate (USDOL ETA 2023). Cost for pallets and bulk bins were taken from online suppliers (bulkbin.com, Grass Valley, California). Estimated labor hours, machine hours, and machine operational costs were supplied by a winter squash enterprise budget created by North Carolina Cooperation Extension unpublished material. Most growers local to the Laurel Springs, North Carolina area produce their pumpkin crop using no tillage. With this management practice, there is no supplemental irrigation used in the field; therefore, the budget does not include irrigation costs. Additionally, this budget analysis does not consider machine ownership costs.

There are several fixed costs in pumpkin production regardless of plant density which include sowing, spray applications, and fertilizers. Sowing is completed with a vacuum planter which does not increase machine hours or labor when increasing plant density. Chemicals and fertilizer are a fixed cost since these are applied on a per area basis; however, high density planting would create more foliage and denser canopy which may require more field management. For example, a post-emergent spray would have a smaller application time frame because the denser canopy would prevent pesticide penetration. Additionally, if fertilizer was applied through fertigation, it may increase with increased plant density if it is a per plant system.

Variable costs for different plant densities include seed cost, packaging materials, harvesting labor, and harvesting machinery operations. More seeds are required per hectare to grow pumpkins at a higher plant density. As plant quantity increases, fruit production also increases, which would require more labor and packing material to harvest the additional fruit. Furthermore, with increased yield, tractor operational costs and labor would increase as it takes more time to collect and haul away fruit from the field to the packaging facility.

Results & Discussion

Results are presented first as fruit bin size measurements, a suggested standardization to fruit size per bin category, and a partial budget analysis per plant density.

Bin Category Fruit Size

Pumpkins increased in diameter, length, and volume as bin size categories increased *Medium*, to *Large*, to *Extra-Large*, to *Jumbo* (Table 2.2). Fruit diameter and volume were chosen as metrics to evaluate fruit size. These were chosen since diameter showed the most separation in the raw data, while volume was a holistic measurement that considered both length and diameter. The mean diameter for each bin category was 24.5 centimeter (cm) for *Medium*, 28.4 cm for *Large*, 31.5 cm for *Extra-Large*, and 35.1 cm for *Jumbo* (Table 2.2). Additionally, volume was 6815 cubic centimeters (cm^3) for *Medium*, 10649 cm^3 for *Large*, 14697 cm^3 for *Extra-Large*, and 20196 cm^3 for *Jumbo*. These results demonstrate that there is separation between diameter and volume for pumpkins that comprise 20, 30, 40 and 55 count bins. The fruit size of these benchmark bin counts could serve as framework to standardize fruit sizes for each bin category.

These data have outliers which highlight flaws with the current system of size accounting. *Jumbo* was the only bin category with volume outliers, which were larger in volume than the normal distribution (Figure 2.1). There is not a bin size category above *Jumbo*, which

means all pumpkins larger than the *Jumbo* bin size range are placed into to the *Jumbo* bin by default. Pumpkins larger than the *Jumbo* category are generally a waste of resource since there is no or limited demand or additional income for the increased fruit size among large commercial change retailers. *Medium* and *Large* bins had outliers when measuring diameter, but not volume, indicating that the lengths of these pumpkins negated any diameter abnormality (Figure 2.1). This underlines the fact that pumpkins are irregularly shaped fruit and measuring more than one metric will help to accurately represent overall fruit size. Other commodities, such as cucumbers and sweetpotatoes, follow this philosophy and specify size standards in terms of fruit length and diameter (USDA AMS 2005, 2018).

Discriminate Analysis of Bins

Since diameter, length, and volume were distinct for each size category, a discriminate analysis was conducted to analyze the accuracy of subjectively sorted fruit into each bin category. *Mediums* were correctly categorized 89% of the time, *Larges* 80%, *Extra-Larges* 64%, and *Jumbos* 87% (Table 2.3). This averages to an overall accuracy of 80% correct placement. For comparison, the watermelon industry size guidelines states that at a specific size range, 5% of the fruit can be under the tolerance and 5% can be over the tolerance, a total of 10% deviation outside of the size tolerance (USDA AMS 2021). *Extra-Large* had the highest number of misplaced pumpkins with 21% being placed in a *Large* bin and 14% being place in a *Jumbo* bin. When pumpkins were misplaced, they were misplaced into a neighboring bin size. Considering *Large* and *Extra-Large* pumpkins, misplaced pumpkins were sized up 33% of the time and sized down 67% of the time. *Medium* and *Jumbo* pumpkins were not considered for this metric since misplaced pumpkins could only be sized up or size down, respectively. The sizes of pumpkin fruit in bin categories are different from one another, but the discriminate analysis showcases

how the current system of visually sorting pumpkins is not satisfactory in separating these differences.

Bin Size Category Standards

Sorting of commercial pumpkin bins can be improved by creating a standard fruit size for each bin size category. Fruit volume would be the optimal metric since it measures the overall fruit size in terms of length and diameter; however, volume is difficult to measure. Pumpkins are large and heavy. Practically, this makes hand measuring both the length and diameter of fruit cumbersome and time consuming. We suggest defining pumpkin bin categories based on fruit weight or by fruit diameter, based on growers' harvesting practice. From the observed pumpkin bins, fruit volume and weight are highly correlated, R^2=0.94. This indicates that fruit weight can successfully capture the overall fruit size even with varying pumpkin shapes. Categorizing fruit by weight would be a simple, easy to implement method. This concept is already in place for watermelon, which are sized according to fruit weight (USDA AMS 2021). Since most pumpkin sorting occurs in the field in North Carolina, we also suggest defining bin categories by fruit diameter. Pumpkin diameter and pumpkin volume are correlated with R^2= 0.94. In some operations, the ground may be uneven and muddy, which is not conducive for weighing. In these instances, we recommend sorting pumpkins by definitive diameter ranges for each bin category. This could be accomplished by using calipers with each diameter range marked and painted with a different color directly on the caliper ruler. Color markings on the calipers could match the color of the fruit size stickers.

Based on our data, we would recommend weight fruit standards of 4 to 5.99 kg for *Medium*, 6 to 7.74 kg for *Large*, 7.75 to 9.99 kg *Extra-Large*, and 10 to 13 kg for *Jumbo* (Table 2.4). For diameter, these same fruit standards are 23.5 to 26.8 cm for *Medium*, 26.9 to 29.9 cm

for *Large*, 30 to 33.6 cm for *Extra-Large*, and 33.7 to 35.5 cm for *Jumbo*. These standards were calculated by taking the mean weights and including one standard deviation for each bin category. This method captures a 68% majority of the sample data points. From here, the standard minimum and maximums were adjusted based on the overlap and or gaps between neighboring bin categories. The weights ranges were then translated into diameter based on the corresponding fruit sizes.

Creating a standard fruit weight for each pumpkin bin category would create a common language for buyers and sellers across the industry. Subjective visual sorting of pumpkins is only 80% effective at sorting fruit and provides merely a description of the product which is less valuable than a defined standard. Introducing weight standards for pumpkin fruit size would equalize the value for pumpkin bins across the market (Spangler 1956). U.S. Standards for a commodity can be introduced if there is need or interest from the industry. The process for implementing a new standard is conducting a study of physical attributes of the commodity, creating a proposal, and posting for public review in the Federal Register (Kader 2002). A standard fruit weight for each bin category would clarify the expectation for growers and allow them to leverage this information to optimize their production.

These recommendations are limited by the sample size of our study. This data set contained 452 pumpkins from one grower with four cultivars. Since there is no current standard, it is highly likely that growers from other regions are categorizing their pumpkins differently by using cultivars and sorting methods not captured here. To build confidence in the pumpkin standards, bin category fruit sizes from additional growers, cultivars, and sorting methods should be surveyed. The standards presented from this research can serve as a starting point for this additional sampling.

Predicting Bin Size Based on Plant Area

The dependent variables of the Production Study and the Commercial Study were compared to predict bin category based on plant area. A least square means test compared the diameter and volume for each plant area to each bin category (Table 2.5). Four plant area fruit diameters were not different from a bin category fruit diameter. From this analysis, we can match the plant area to a bin category by the expected fruit diameter. The remaining four plant areas were different from all bin fruit sizes, signifying that their fruit diameter did not correspond to the fruit diameter from any of the bin categories. In these scenarios, the bin category with the closest diameter to the plant area fruit diameter was selected. This was analysis was repeated for volume. For diameter and volume, plant areas of 2.8 and 3.7 m^2 were classified as *Jumbo*, the plant area of 1.9 m^2 was classified as *Extra-Large*, and the plant area of 0.9 m^2 was either *Large* or *Extra-Large*, depending on row width. By changing the row width of a 0.9 m^2 plant area from 3.0 m to 1.5 m, the bin category increases from *Large* to *Extra-Large* (Table 2.5). As previously noted, *Large* pumpkins are a 40-count bin and *Extra-Large* pumpkins are a 30-count bin. If different row widths are at parity for fruit quantity, the 1.5 m row width would fill more bins simply by being categorized as *Extra-Large* compared to *Large*. This is because *Extra-Large* pumpkins only need 30 fruit to fill a bin, while *Large* pumpkins need 40 fruit to fill a bin. A study from Reiners and Riggs (1999) reports increased fruit quantity by reducing row width from 3.6 to 1.8 m, suggesting an even wider difference between the row width bin quantities. Both plant areas of 2.8 and 3.7 m^2 produced a *Jumbo* pumpkin. This means that there is no increased fruit size by increasing plant area above 2.8 m^2. Several studies indicate that fruit quantity decreases with increased plant area (Weiner 1990, Reiner and Riggs 1999, El-Sayed 2011). The

2.8 m^2 would have higher economical returns compared to the 3.7m^2 since both areas produce Jumbo pumpkins and the 2.8 m^2 would have more fruit per area.

Some of the pumpkin volumes from the production study were outside of the bounds of the categorized bin volumes and vice versa. The fruit volume for the 3.7 m^2 plant area with a 1.5 m row width was 21,399 cm^3 which was larger than the mean fruit volume for *Jumbo* pumpkins, at 20,196 cm^3. This indicates that a plant area of 3.7 m^2 produces pumpkins larger than the commercial bin range. None of the pumpkins from the production study were categorized as a *Medium* pumpkin. The smallest plant area of 0.9 m^2 produced a *Large* pumpkin. Since fruit size decreases with decreased plant area (Brinen et al. 1979, Reiners Riggs 1997, El Sayed et al. 2011), a smaller plant area would be required to grow a *Medium* pumpkin with the 'Kratos' cultivar. Since 0.9 m^2 is already below the recommended plant area, switching to another cultivar that produces smaller fruit may be more adventitious (Kemble et al. 2022). Without having *Medium* pumpkins in this study, we cannot provide plant area recommendations for this bin category. This is a limitation of this study, and further studies would have to be completed to provide this information.

Partial Budget Analysis

Fixed costs for pumpkin production are field preparation, cultivation, field maintenance, totaling \$3134 · ha^{-1} (Table 2.6A). Since this partial budget analysis is per hectare, all costs that are on a per area basis are a fixed cost. Field preparation is estimated to cost \$990 · ha^{-1} which include soil testing, pre-emergence, lime, and pre-plant fertilizer. During the growing season, the main input costs are pesticide applications. Labor costs for planting and field maintenance would remain a fixed cost at \$777 · ha^{-1}. Lastly, estimated machinery operation costs, including a 50 horsepower (HP) tractor, plow, boom sprayer, and vacuum planter would cost \$216· ha^{-1}.

Estimated fruit size and fruit quantity from the production study allow us to estimate the bin category and bin quantity for each plant area (Table 2.6B). The plant areas of 3.7, 2.8, 1.9, and 0.9 m^2 are equivalent to plant densities of 2691, 3588, 5382, and 10764 plants · ha^{-1} respectively. As stated before, as plant area decreases, fruit number per hectare increases and fruit size decreases. Using the 1.5 m row width, the plant areas of 3.7 and 2.8 m^2 produce *Jumbo* fruit and the plant areas of 1.9 and 0.9 produce *Extra-Large* fruit. *Jumbo* pumpkins pack 20 fruit per bin while *Extra-Large* pumpkins pack 30 fruit per bin. From the 2021 production study, plant areas of 0.9, 1.9, 2.8, and 3.7 m^2 produced 9149, 7097, 5046, and 4676 fruit · ha^{-1} respectively. Keeping the same plant area order, the projected bin yield was 305 *Extra-Large* bins, 237 *Extra-Large* bins, 252 *Jumbo* bins and 234 *Jumbo* bins.

The variable costs for plant area include seed costs, harvest packaging material, harvest labor, and machine operations (Table 2.6C). Cost for seed increased from $340 to $1358 when decreasing plant area from 3.7 to 0.9 m^2. Since decreased plant area leads to increased fruit yield, more bins and pallets are required for harvest with higher plant densities. These packaging costs increased by $2,676 from the lowest to highest plant density. With higher fruit yield, labor costs will increase as more time and workers are required to harvest the additional fruit. Furthermore, machine operation costs will increase as more hours are required to collect, harvest, and haul pumpkins out of the field. Overall, variable costs start at $10427 · ha^{-1} with the plant area of 3.7 m^2, a density of 2691 plants · ha^{-1}, and increase to $17,925.20 · ha^{-1} for the plant area of 0.9m^2, density of 10764 plants · ha^{-1}.

Pumpkins were sold at an average price of $190 per bin across all bin size categories in 2022 (USDA ERS 2022). From the fixed costs, variable costs, and yield estimates, the highest profiting plant area was 0.9 m^2, or 10765 plants · ha^{-1}, with a profit of $36891· ha^{-1}(Table 2.6D).

The lowest profiting plant area was 1.9 m^2, or 5382 plants · ha^{-1}, with a profit of \$29749· ha^{-1}. This difference in profit comes strictly from fruit quantity since both plant areas produce fruit that would be categorized as *Extra-Large*. The 0.9 m^2 spacing produces 68 more bins per hectare compared to 1.9 m^2. It is economically beneficial for growers to maximize fruit quantity within plant areas producing the same fruit size. In another example, the 3.7 m^2 plant area produced 234 *Jumbo* bins, profiting \$30899 · ha^{-1}. Comparing this to the 0.9 m^2 yield, growing larger pumpkins does not always lead to higher profits. Instead, profit is based on a combination of fruit size, categorical bin count, and fruit quantity per hectare. Here it is more financially beneficial to grow *Extra-Large* pumpkins in a smaller plant area than *Jumbo* pumpkins in a larger plant area. If growers are producing *Jumbo* pumpkins, they should consider reducing plant area for their next growing season to avoid wasting additional inputs.

Growers can use this partial budget to maximize their profit within the constraints of their operations. Equipment, land, or storage facility may limit growers' production to a certain row width, total plant area, or bin quantity. This partial budget analysis will help producers adjust other factors within their operations to maximize profit strategically through bin category and quantity.

Conclusion

Commercial practices of visually sorting pumpkins into categorical bin sizes are currently 80% effective. Standardizing fruit size for each bin category would create a common language among buyer and sellers. We suggest using a defined weight or diameter range for each bin category. These methods were chosen because they would be easy to implement with current harvest practices and replicate across the industry. A limitation of the commercial bin study is the sample size of one grower which used one sorting practices and only a few cultivars. To

create a more robust recommendation, additional data should be collected on different growers, sorting practices, and cultivars.

Growers can use these standard fruit sizes to predict yield in terms of bin category and quantity based on their plant area. Data from the production study estimate that plant areas of 0.9 and 1.9 m^2 produce *Extra-Large* pumpkins, while 2.8 and 3.7 m^2 produce *Jumbo* pumpkins. As stated in the discussion, a limitation of this study is that the fruit size range from the production study did not align with the fruit size range from the commercial bin study. With this gap, the bin sizes of *Medium* and *Large* cannot be correlated to a plant area while using a 3.0 m row width. Further research with other plant areas will have to be conducted to predict a plant area for growing *Medium* and *Large* pumpkins.

Through completing a partial budget analysis on plant area, growers can maximize profits on a per hectare basis by growing *Extra-Large* bins with a 0.9 m^2 plant area and profit \$36,890 ha^{-1}. Growers can use this analysis to make informed decision on plant density by understanding the associated variable costs and predicted income at each plant density. Through these suggestions, pumpkin producers can maximize their production and their profits.

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Table 2.1. Summary table of eight plant areas (0.9, 1.9, 2.8, and 3.7 m^2) and four commercial bin size categories (*Medium*, *Large*, *Extra-Large*, and *Jumbo*) from pumpkin production and commercial bin data. For simplicity these data are labeled as Treatments 1–12.

Study	Treatment	Plant Spacing (m)	Plant Area (m^2)	Bin Category
Production	1	3.0 x 0.3	0.9	N/A
Production	2	3.0 x 0.6	1.9	N/A
Production	3	3.0 x 0.9	2.8	N/A
Production	4	3.0 x 1.2	3.7	N/A
Production	5	1.5 x 0.6	0.9	N/A
Production	6	1.5 x 1.2	1.9	N/A
Production	7	1.5 x 1.8	2.8	N/A
Production	8	1.5 x 2.4	3.7	N/A
Commercial Bin	9	N/A	N/A	‘Medium’
Commercial Bin	10	N/A	N/A	‘Large’
Commercial Bin	11	N/A	N/A	Extra-Large’
Commercial Bin	12	N/A	N/A	‘Jumbo’

Table 2.2. Pumpkin fruit diameter, length, and volume from commercially sorted bin size categories (*Medium*, *Large*, *Extra-Large*, and *Jumbo)*. Each fruit size has a corresponding bin count which refers the approximate number of fruit that will fit into the bin based on fruit size.

Commercially Sorted Packaging		**Fruit Measurements**		
Bin Count	**Fruit Size**	**Diameter (cm)**	**Length (cm)**	**Volume (cm^3)**
55 – 65	Medium	24.5 a	21.4 a	6815 a
40	Large	28.4 b	25.3 b	10649 b
30	Extra-Large	31.5 c	28.0 c	14697 c
20	Jumbo	35.1 d	31.0 d	20196 d

Note: Comparisons are made within each column for each variable.

Table 2.3. Discriminate Analysis for pumpkins visually sorted into four commercial bin size categories (*Medium*, *Large*, *Extra-Large*, and *Jumbo).*

	Number of Observations and Precent Classified into each Bin Size				
	Medium	**Large**	**Extra-Large**	**Jumbo**	**Total**
Medium	160 88.89%	20 11.11%	0 0.00%	0 0.00%	180 100.00%
Large	12 10.17%	94 79.66%	12 10.17%	0 0.00%	118 100.00%
Extra-Large	0 0.00%	19 21.11%	58 64.44%	13 14.44%	90 100.00%
Jumbo	0 0.00%	0 0.00%	8 12.50%	56 87.50%	64 100.00%
Total	172 38.05%	133 29.42%	78 17.26%	69 15.27%	452 100.00%

Table 2.4. Recommended fruit size weight and diameter standards for four pumpkin commercial bin size categories (*Medium*, *Large*, *Extra-Large*, and *Jumbo*).

	Recommended Bin Ranges			
	Medium	Large	Extra-Large	Jumbo
Minimum Weight (kg)	4.00	6.00	7.75	10.00
Maximum Weight (kg)	5.90	7.74	9.90	13.00
Minimum Diameter (cm)	23.50	26.90	30.0	33.70
Maximum Diameter (cm)	26.80	29.90	33.60	35.50

Table 2.5. Prediction of the commercial pumpkin bin size category (*Medium*, *Large*, *Extra-Large*, and *Jumbo*) for different plant areas and row widths based on fruit diameter and fruit volume.

Production Study Treatments		**Predicted Bin Category based on Fruit Size**			
Plant Area	**Row Width**	**Diameter**	**p Value**	**Volume**	**p Value**
0.9	3.0	Large	0.8045	Large	0.0127*
1.9	3.0	Extra-Large	0.0328*	Extra-Large	0.0001*
2.8	3.0	Jumbo	0.0004*	Jumbo	0.0010*
3.7	3.0	Jumbo	0.0112*	Jumbo	0.1771
0.9	1.5	Extra-Large	<0.0001*	Extra-Large	0.0064*
1.9	1.5	Extra-Large	0.3771	Extra-Large	0.0210*
2.8	1.5	Jumbo	0.1100	Jumbo	0.3012
3.7	1.5	Jumbo	0.6058	Jumbo	0.0776

Note: *indicates that plant area fruit size and bin category fruit were different from one another.

Table 2.6. Partial budget analysis for ‘Kratos’ pumpkins at densities of 2691, 3588, 5382, and 10746 plants per hectare for (A) Fixed Costs, (B) Yield Estimations, (C) Variable Costs, and (D) Net Returns.

Table 2.6A. Fixed costs for pumpkin production per hectare at densities of 2691, 3588, 5382, and 10746 plants per hectare.

Item	Unit	Quantity	Price/Unit	Costs
Field Preparation & Cultivation				
Soil Test	test	1.00	$ 25.00	$ 25.00
Lime	tons	1.85	$ 36.00	$ 66.60
Pre-plant Fertilizer: 10-10-10	tons	1.11	$ 610.00	$ 677.10
Pre-Emergence Herbicide				
Curbit 3EC	liter	2.33	$ 12.19	$ 28.40
Gramoxone Max	liter	1.16	$ 31.94	$ 37.05
Roundup Weathermax	liter	1.16	$ 31.94	$ 37.05
Command 4EC	liter	1.16	$ 17.03	$ 19.75
Select 2EC	liter	1.16	$ 85.17	$ 98.80
Field Maintenance				
Fertilizer - Sidedress	tons	0.13	$ 610.00	$ 79.30
Fungicides	application	8.00	$ 74.10	$ 592.80
Insecticides	application	8.00	$ 37.05	$ 296.40
Machinery Operations				
Field Preparation & Cultivation - Tractor	hours/ha	28.4	$ 4.50	$ 127.80
Field Preparation & Cultivation - Plow 3- 16"	hours/ha	4.9	$ 2.00	$ 9.80
Field Preparation & Cultivation - Planter	hours/ha	2.47	$ 1.50	$ 3.71
Field Maintenance - Tractor	hours/ha	13	$ 4.50	$ 58.50
Field Maintenance - Boom Sprayer	hours/ha	11.1	$ 1.50	$ 16.65
Labor				
Field Preparation & Cultivation	hours	15.07	$ 14.91	$ 224.69
Field Maintenance - Tractor	hours	37.05	$ 14.91	$ 552.42
Other				
Crop Insurance	ha	1	$ 182.65	$ 182.65
Total Fixed Costs				**$ 3,134.57**

Table 2.6B. Yield estimation for both commercial pumpkin bin size category (*Medium, Large, Extra-Large, Jumbo*) and quantity for densities of 2691, 3588, 5382, and 10746 plants per hectare.

Yield Estimation	**Plant Density (plants/ha)**			
	2691	**3588**	**5382**	**10764**
Plant Area (m2)	*3.7*	*2.8*	*1.9*	*0.9*
Fruit Size	Jumbo	Jumbo	Extra-Large	Extra-Large
Fruit/Bin	20	20	30	30
Fruit Number	4676	5046	7097	9149
Expected Bin Quantity	**234**	**252**	**237**	**305**

Table 2.6C. Variable Costs for pumpkin production per hectare at densities of 2691, 3588, 5382, and 10746 plants per hectare.

Item	**Unit**	**Quantity**	**Price/Unit**	**Cost by Plant Density (plants/ha)**			
				2691	**3588**	**5382**	**10764**
Field Preparation, Cultivation							
Treated Seeds	thousand	1	$ 126.17	$ 339.52	$ 452.70	$ 679.05	$ 1,358.22
Harvest							
Fiberboard Bins	case	42	$ 1,079.00	$ 6,011.46	$ 6,473.88	$ 6,088.53	$ 7,835.45
Pallets - Repaired Grade A	pallet	1	$ 12.00	$ 2,808.00	$ 3,024.00	$ 2,844.00	$ 3,660.00
Labor Hours: Harvesting	plants/hour	51	$ 14.91	$ 786.72	$ 1,048.96	$ 1,573.44	$ 3,147.18
Labor Hours: Hauling	plants/hour	119	$ 14.91	$ 337.17	$ 449.56	$ 674.33	$ 1,348.79
Machinery Operations							
Harvest & Hauling- Tractor	plants/hour	169	$ 4.50	$ 71.65	$ 95.54	$ 143.31	$ 286.64
Wagons, Trailers	plants/hour	169	$ 0.25	$ 3.98	$ 5.31	$ 7.96	$ 15.92
	plants	5000	$ 126.68	$ 68.18	$ 90.91	$ 136.36	$ 272.74
Total Variable Costs				**$ 10,426.68**	**$ 11,640.86**	**$ 12,146.98**	**$ 17,924.94**

Table 2.6D. Summary of income, total costs, and net returns for pumpkin production per hectare at densities of 2691, 3588, 5382, and 10746 plants per hectare.

Item	Unit	Quantity	Price/Unit	Income by Plant Density (plants/ha)			
				2691	3588	5382	10764
Income							
Categorized Commercial Bin	0.9 m bin	1	$ 190.00	$ 44,460.00	$ 47,880.00	$ 45,030.00	$ 57,950.00
Total Costs				$ 13,561.15	$ 14,775.33	$ 15,281.45	$ 21,059.41.
Net Returns				**$ 30,898.85**	**$ 33,104.67**	**$ 29,748.55**	**$ 36,890.59**

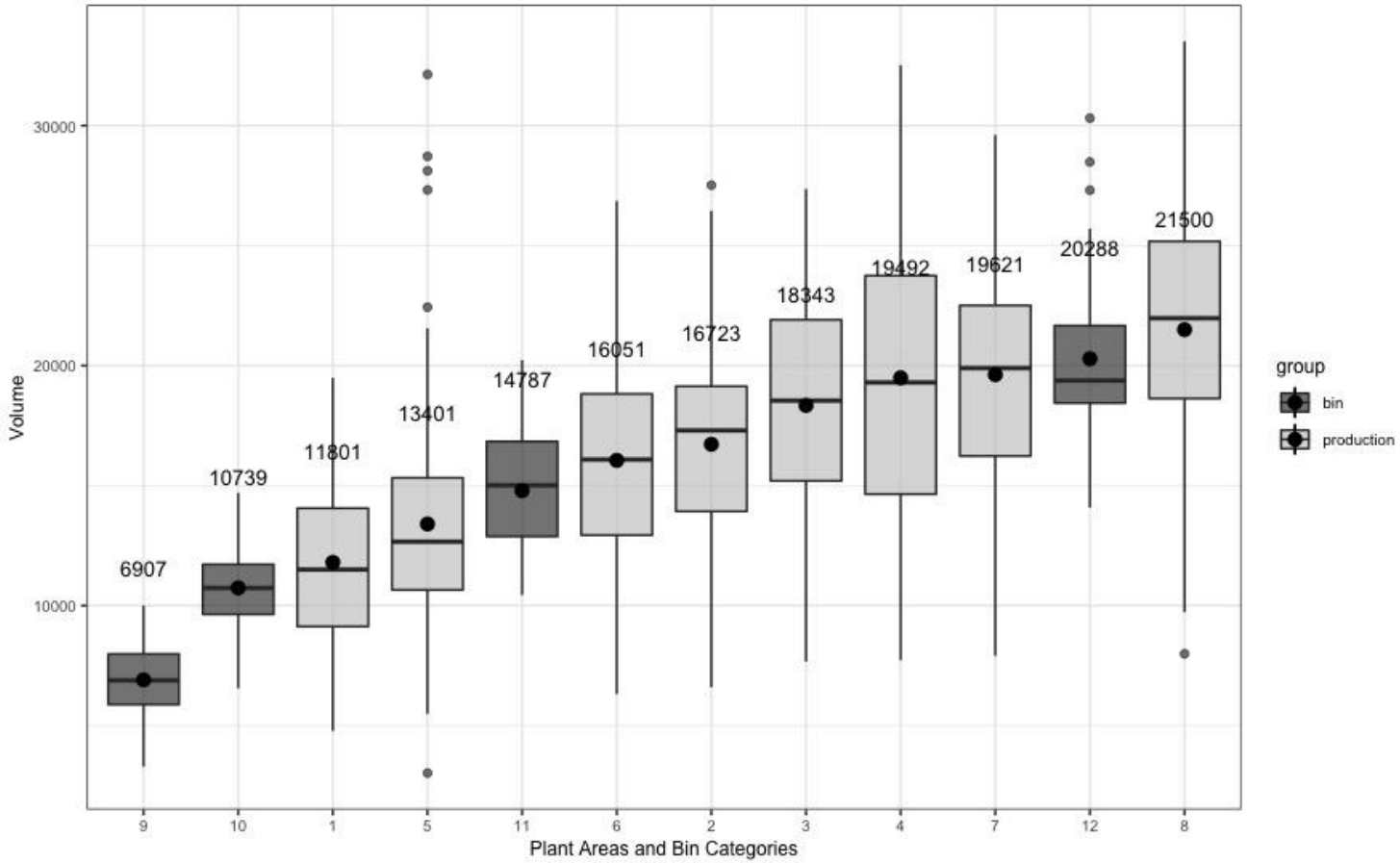

Figure 2.1. Volume (cm^3) comparison of pumpkins from eight plant areas and four commercial bin size categories from pumpkin production data and commercial bin data. Plant areas are 0.9, 1.9, 2.8, and 3.7 m^2 with 3.0 m row width (Treatments 1 – 4 respectively) and 1.5 m row width (Treatments 5 – 8 respectively). Commercial bin size categories in include *Medium*, *Large*, *Extra-Large*, and *Jumbo* (Treatments 9-12 respectively). A treatment summary is provided in Table 2.1.
Note: Means are listed on plot and represented with large dot.

CHAPTER 3

Detecting and Measuring Pumpkin Yield with Commercialized Unmanned Aerial Vehicles and Object Detection Models

(In the format appropriate for submission to a ASABE Journal)

Abstract

Estimating pumpkin fruit yield is important for growers to market their crop and secure appropriate labor and packing supplies for harvest. Additionally, commercial pumpkins are sold in categorical bins based on fruit size and knowing the expected bin categories will further aid the grower at harvest time. The only historical method for counting the whole field yield is manually counting which is time consuming. A study was completed to test the accuracy of predicting pumpkin (*Cucurbita sp.)* fruit quantity and size using commercially available Unmanned Aerial Vehicle (UAV) and object detection model. An UAV was flown two separate years over a mature pumpkin field. These images were analyzed using Solvi Plant AI, an object detection software and assessed for detecting and measuring pumpkins. The detection model had an overall accuracy of 99% with precision values ranging from 0.9 to 1, recall 0.86 to 1 and F1 score 0.92 to 1. Fields with a high density of fruit decreased in accuracy with the model detecting two adjacent fruits a one, resulting in false negatives. For measuring fruit size, the detection model overestimated fruit diameter by a mean estimate of 1.1 cm. A total of 43% of the model's measurements were within 1 cm of the ground truth measurement. Using UAV-based images and image classification systems are a powerful resource for counting pumpkins and estimating over fruit yield. Estimating fruit size is not as accurate and would require post processing method to achieve a higher level of accuracy.

Introduction

Precision agriculture is a management strategy that collects spatial and temporal data on production systems to improve production efficiency, quality, and sustainability (ISPA 2021, Shannon et al. 2018). This term was first coined in 1990 by Montana State University replacing the term "site-specific agriculture" (Oliver 2010). Precision agriculture is a system-based

approach of using various technologies to measure crop data, analyze the data, and make informed decisions with targeted crop management. By measuring and accounting for field spatial variation, growers shift from whole field management to sub-field management, hypothetically optimizing yield and minimizing environmental impact (Shannon et al. 2018). The power of precision agriculture is created by connecting data to specific locations on the earth's surface. This management strategy is primarily made possible through the development of the Global Positioning System (GPS). Since GPS, a multitude of technologies have been invented or been used for precision agriculture such as yield monitoring and mapping, variable rate application, and remote sensors (Davis et al. 1998).

Unmanned or Uncrewed Aerial Vehicles (UAVs), commonly called drones, are a remote sensing technology that have become popular in precision agriculture due to their flexibility and wide range of application (Everarts 2008). A UAV functions as a system of the remote pilot with the controller, the unmanned aircraft, and the communication between the two. The two main types of UAVs are fixed-wing and multi-rotor which vary in aero-dynamic features. The UAV will have a payload, or a tolerable weight the aircraft can carry, which is often a sensor such as a Red Green Blue (RGB) or multispectral camera.

UAVs and RGB cameras are beneficial to agriculture by efficiently collecting in-season aerial pictures of a crop and translating them into useful crop information. UAVs reduce labor since large areas of crops can be assessed at one time for multiple factors as opposed to manually collecting individual sets of data. Compared to other aerial systems, UAVs provide more flexibility by deploying quickly, which proves useful when considering ever-changing weather conditions or unexpected crop concerns. In recent years, UAVs have become more affordable and easier to operate, increasing their popularity in precision agriculture (Ferguson 2018).

Once UAV images are collected, they are transformed into meaningful statistics through image analysis. Common plant physiological factors analyzed with UAV images are plant health, disease detection, and yield estimation (Kakarla 2022). Individual UAV images are stitched together to create one cohesive image of the field, an orthomosaic, which is a large raster of individual pixels. From here, the image can be analyzed through machine learning models, Geographic Information Systems (GIS), or simple visual observation.

Supervised Object-Based Image Classification is a type of machine learning that translates UAV images into information on user identified objects (Esri Academy 2022). This classification process sorts the raster's pixels into categorized groups, based on the pixel's shape, texture, and neighbors. The pixels are sorted based on human specification which are trained on a machine learning software (Esri Academy 2022). Once the software is trained, it can identify and provide a portfolio of information on the user identified objects. Agricultural applications for object detection models include automating stand counts, counting open blooms and estimating fruit yield.

Pumpkins (*Cucurbita sp.)* are an important autumn crop in the United States (U.S.). In 2021, the U.S. produced 991.6 million kilograms (kg) of pumpkins with a value of $233 million (ESMIS USDA 2022). The top uses for pumpkins are home decorations, seasonal food products, and Halloween jack o' lanterns (USDA ERS 2015). Before harvest, pumpkins have a dense canopy, hiding fruit size and quantity. Pumpkins, for large commercial acreage, are typically a one-time harvest crop since vines are destroyed in the harvesting process. Commercially, pumpkins are packed into pallet-sized bins based on fruit size. These bins are labeled as *Medium*, *Large*, *Extra-Large*, and *Jumbo*; however, the exact fruit size and bin sorting practices vary based on the operation.

Pre-harvest yield estimations are vital for growers to prepare accurately for harvest and to market their crop appropriately (Wittstruck 2020). Harvesting is an expensive and stressful time for growers with scheduling labor, ordering correct quantities of packaging material and timing the harvest for optimal fruit ripeness. Furthermore, pumpkins are sold in bins based on fruit size. Growers can optimize the commercialization of their pumpkins by having an accurate estimation of both the quantity and size of their crop yield.

UAVs provide a non-destructive, in-season method for yield estimation for crops. This has been tested and assessed for many crops including cotton, citrus fruit, and strawberry blooms (Yeom et al. 2018, Chen 2019, Apolo-Apolo et al. 2020). For pumpkins, two studies have been completed which show accurate detection of pumpkins through UAV and machine learning methods (Wittstruck et al. 2021, Midtiby and Pastucha 2022). The first used pixel-based image classification to compare 140 ground truth pumpkins to UAV-based RGB imagery (Wittstruck et al. 2021). The UAV images and classification software detected 95% of the field sample pumpkins. Fruit weight estimation have a correlation of r=0.84 compared to ground truth data. Another study examined the detection of pumpkin yield through analyzing different segmentation thresholds (Midtiby and Pastucha 2022). Results for detecting pumpkins are above 0.95 for precision, recall and F1 scores. These results were validated by testing 5% of each orthomosaic area in individual 10 x 10 m squares.

There is currently a gap in the literature for assessing the accuracy of UAV-based pumpkin yield estimations to ground truth data on a large scale. Since UAV yield estimation will be used over multi-hectare fields, a large sample size is needed to build confidence in the validity of the method. Other studies use manually counted targets from a UAV image as the control data

set instead of a ground truth data set. Using a ground truth data set as the control better represents the current method of hand counting and measuring fruit for yield estimation.

Additionally, previous UAV yield estimation studies assess the accuracy of object detection, but do not assess the accuracy of target measuring. This capability is now available through software such as Solvi but has not been evaluated for accuracy in horticultural settings. There is no published material on the comparison of a pumpkin diameter measured by hand and measured from UAV images. This yield metric would be useful to growers since in addition to knowing the number of fruit in a field, a grower also needs to know the bin size categories of those fruits.

The objective for this study is to assess the accuracy of UAV-based imagery for pumpkin yield estimation through supervised object-based image classification. Yield estimation includes both detecting fruit and measuring fruit size.

Materials and Methods

Field Preparation

The study was conducted during 2020 and 2021 in Laurel Springs, North Carolina (lat. 36.398789°N, long.81.307266W°) at the North Carolina Department of Agriculture & Consumer Services Upper Mountain Research Station. The field site consisted of Toxaway silt loam (fine-loamy, mixed, superactive, nonacid, mesic Cumulic Humaquepts) and had an annual rye cover crop sown prior to the study (USDA NRCS 2022). The field was prepared with discing, rototilling, and rolling, which imitated no-tillage. There were two pre-plant fertilizers, 112 kg · ha^{-1} of 0N-0P-50K and 329.3 kg · ha^{-1} of 17N-17P-17K, and a side dress of 39.2 kg · ha^{-1} of 15N-15P-15K when the plants were vining. This field was organized for a production study that assessed plant density and fruit yield. The study was randomized complete block design with 24

plots in 2020 and 32 plots in 2021, a total of 56 plots. Plots were 12.2 m in length with 4 rows and had either 3.0 m or 1.5 m row width spacing. The cultivar for this study was 'Kratos' (*Cucurbita pepo*) which is the most popular carving pumpkin commercially produced in the U.S. (Froese J, personal communication). Seeds were direct seeded on 5 June 2020 and 17 June 2021 and harvested when fruit reached maturity on 1 October 2020 and 23 September 2021. In 2020, the growing season had an average temperature of 18.9° C and a total rainfall accumulation of 50.0 centimeter (cm) while 2021 had an average temperature of 19.3° C and total rainfall accumulation of 44.1 cm (NCARS 2022).

Data Collection

Data were collected on mature, blemish free fruit on the day of harvest for each year. The harvest and image analysis area were the center 25% area of each plot. This amount was chosen to ensure a consistent competitive effect for the production study. Each plot harvest area was measured, staked, and outlined with colored marking tape. Due to the two different row width spacings, the harvest area alternated between 37.2 m^2 (6.1 m by 6.1 m) for the 3.0 m row width spacing and 18.6 m^2 (6.1 by 3.0 m) for the 1.5 m row width spacing. Ground truth data were collected on pumpkins within each harvest area. Data included weight, length, which is the distance from stem to blossom end, and diameter, which is the largest distance across the fruit perpendicular to the length. Pumpkins were marked with printed adhesive labels which served as unique number identifiers. Foliage inside of the marked area was flattened to make pumpkins completely visible from above. This differs from commercial pumpkin production which may spray fields with a chemical application to reduce canopy coverage (Birdsell T, personal communication). Immature pumpkins were not included in this data set. Pumpkins were classified as mature if the fruit was orange or would ripen to orange off the vine. Anything less

mature than this was classified as immature. Some of the classified mature pumpkins were mainly green at the time of harvest but were mature enough to change to an orange color by the time of sale.

UAV Specifications and Operation

A DJI Phantom 4 Pro V2 with integrated Phantom Pro V2 RGB camera (DJI, Shenzhen, China) was used to collect images the day of harvest. Camera specifications include a 2.5 cm complementary metal-oxide-semiconductor (CMOS) sensor, with 20 megapixel density, and a focal length of 8.88 mm. All image collection flights occurred between 10:00 h and 14:00 h local time during comparable weather conditions that facilitated proper image collection. Images for orthomosaic processing were collected with a 70% overlap along direction of travel and 80% side overlap. The resulting ground sampling distance (GSD) was 0.84 cm pixel^{-1} at approximately 30.5 m above ground level (AGL). An additional high-resolution image collection flight occurred each year to capture legible images of the unique label identifiers applied to each mature fruit. These discrete images were collected over each plot at 15.3 m AGL for a 0.41 cm pixel^{-1} GSD. Flights were planned and executed using the Pix4Dcapture (Pix4D S.A., Prilly, Switzerland) mobile application on a supported iOS (Apple, Inc., Cupertino, CA) device.

Image Analysis

Imagery was stitched and analyzed with commercially available tools. The approach to this project was to utilize systems currently available to users of these technologies. The primary focus was on the applicability of the data to harvest-related decision making. The collected UAV images were stitched together using Pix4Dmapper (Pix4D S.A., Prilly, Switzerland) on a local desktop computer at default settings to create an orthomosaic image. Pumpkin fruit identification, counting, and measurement was conducted in Solvi (Solvi AB, Gothenburg,

Sweden). Solvi is a cloud-based agricultural UAV imagery processing analysis platform with an artificial intelligence (AI) based plant counting and measurement service called Plant AI™. The two orthomosaic images, one from each year, were uploaded to Solvi for supervised object-based image classification. Following the program's prompting, the software was trained to detect pumpkins by having the user identify all desired targets within a small portion of the orthomosaic. In this case, all mature fruits within one randomly selected plot were identified as training targets. The rest of the image was then analyzed with the classification model and the results were then returned and visualized. The user could then approve the results or re-train the model until satisfied with classification performance. In this analysis, the first training result was accepted. QGIS Long Term Release 3.22.4-Bialowieza (Open Source Geospatial Foundation, Chicago, Illinois, USA) was used for further image processing and data management which allowed comparison of Solvi's analysis to the ground truth data. High resolution plot images were georeferenced onto the orthomosaic for reading and referencing the unique number identifiers on each pumpkin.

Statistical Analysis

Data were analyzed using SAS Studio (SAS, Cary, North Carolina). A paired t-test was completed to test the difference for mean fruit count and diameter measurement between ground truth data and UAV based detection model data. A Bland Altman plot, which compares the difference between two methods, was used to measure heteroscedasticity. Metrics of precision, recall, and F1 scores were used to evaluate the effectiveness of the model. These model performance metrics quantify the model's ability to find and identify pumpkin fruit. Precision is the ratio of the true positives detected by the model to all positives detected by the model. Recall is the ratio of the number of true positives detected by the model to all ground truth positives in

the data set. F1 is an additional metric used in binary classification to test a method's overall accuracy (Kulkarni et al. 2020). Accuracy is the comparison of the detection model count to the ground truth count. A true positive (TP) was defined as when the model detected a ground truth pumpkin, a false positive (FP) was when the model detected an object other than a ground truth pumpkin, and a false negative (FN) was when the model did not detect a ground truth pumpkin. True negative (TN) was not defined or quantified as it was not used in any of the model performance calculations.

$$Precision = \frac{True\ Positive}{True\ Positive + False\ Positive}$$

$$Recall = \frac{True\ Positive}{True\ Positive + False\ Negative}$$

$$F1\ Score = 2\left(\frac{Precision * Recall}{Precision + Recall}\right)$$

$$Accuracy = \frac{Machine\ Learning\ Count}{Manual\ Count}$$

Results and Discussion

Detecting Pumpkins

The detection model in Solvi had mean precision, recall, and F1 scores greater than 0.95 for detecting a total of 1,034 mature pumpkin fruits in fifty-six plots (Table 3.1) The lowest precision in a single plot was 0.90, meaning that 90% of the detected targets were ground truth pumpkins and 10% of the detected targets were false positives. Forty-nine of the plots had a precision score of 1, indicating that all the targets detected were ground truth pumpkins and there were no false positives. There were 13 unique instances of false positives across the remaining seven plots (Figure 3.1). From these 13 instances, three of the targets detected were part of leaves, two were portions of a very immature fruit, and eight were in the immediate vicinity of the colored tape used to mark plot perimeters. The tape used in this study was brightly colored to

increase visibility. A more neutral color such as green or brown could be used in the future to prevent these errors. These results were similar to a UAV image study where strawberry blooms were detected with a precision of 0.76 to 0.91 with a Faster RCNN detection network. (Chen et al. 2019). Additionally, a RetinaNet deep convolutional neural network (CNN) identified melons from UAV-based images at a precision of 0.92 (Kalanatar et al. 2020).

The recall per plot ranged from 0.86 to 1.0 with an overall mean of 0.99. The lowest observed recall value of 0.86 was on a single plot. Out of the 56 plots, there were 44 plots where every ground truth pumpkin was detected. On the remaining twelve plots, 17 instances of false negatives occurred (Figure 3.2). Thirteen of these false negatives occurred when a pumpkin was lying adjacent to another pumpkin. In these cases, the detection model grouped both pumpkins together as one target. This occurred for both mature orange pumpkins and immature green pumpkins. This issue has been observed with other UAV based image analysis and was solved through additional processing steps. For example, a study analyzing Hokkaido pumpkins experienced this same issue and added a splitting function to differentiate two joint objects (Wittstruck 2021). Another example of a false negative from the analysis happened when the fruit was covered by the leaf canopy, occluding the fruit. The remaining two instances occurred when the model failed to detect a single visible pumpkin. One of these pumpkins was a small, misshapen fruit. The other pumpkin was missing the white adhesive label, most likely blown off by the wind. Without a label or conforming to the typical pumpkin shape, these fruits may not have met the object detection criteria used to categorize pumpkins, leading to the false negative. The pumpkin without the label may reveal a limitation of this study. All fruit that was used as ground truth data had a white rectangular label on the fruit. It is possible that the detection model

used the white label as part of the algorithm to detect pumpkins. A future study assessing the accuracy of detecting pumpkins without labels could test this hypothesis.

The lowest F1 score was 0.92. Thirty-nine of 56 plots had an F1 score of 1 which means the software was 100% accurate in these plots by detecting all true positives and only true positives. The overall accuracy across all plots was 99% (Table 3.2). These results are similar to precision, recall, and F1 scores of citrus yield estimated using UAV images which had a performance of greater than 0.90 for recall, precision, and F1 scores over three years (Apolo Apolo et al. 2020). Another UAV methods study reported F1 scores of 0.90 or greater when detecting melon fruit yield (Kalanater et al. 2020).

Plant Density Interaction

The plots used in this study were primarily grown for a production study investigating fruit yield at plant densities ranging from 2691 to 10764 plants ha^{-1}. For pumpkins and other cucurbit crops, a higher plant density results in a higher fruit number per area (Weiner 1990, Reiners and Riggs 1999, El Sayed 2011). For reference, the fruit yield from the 10764 plant $\cdot ha^{-1}$ density was 12,648 fruit $\cdot$ ha^{-1} in 2020 and 9,149 fruit$\cdot$ ha^{-1} in 202. The fruit yield from the 2691 plant ha^{-1} density was 4,081 fruit $\cdot$ ha^{-1} in 2020 and 4,676 fruit $\cdot$ ha^{-1} in 2021. As mentioned earlier, pumpkins closely adjacent to another pumpkin were sometimes counted as a single target, creating false negatives. An analysis of variance (ANOVA) was conducted to analyze if the plant density interfered with the detection model accuracy (Table 3.2). Plant density was significant ($p=0.001$) with 10764 plants $\cdot$ ha^{-1} plots having a greater error rate than plots with 2,691 plants $\cdot$ ha^{-1}. The increase in pumpkin fruit yield from higher plant densities generated more occurrences of fruit lying closely adjacent, increasing the error rate of the detection model. Even though the error rate increased at high fruit density, the model was still 90% accurate in

crop identification. If a higher accuracy is required, error rate could be decreased with additional post processing such as splitting large or atypical targets according to parameters set by the analyst.

A paired t-test comparing model detected true positives to ground truth pumpkins reported a difference between the methods for estimating fruit number ($p=0.001$). Even though the methods were different, the UAV method can still be a practical method to estimate yield. Across all plant densities, the detection model was 100% accurate for 70% of the plots. The error rate was greater than 5% for only two of the plots (Table 3.2). A second paired t-test was completed removing the 10764 plants $\cdot$ ha^{-1} densities and found the methods not different ($p=0.160$). This indicates that at a plant density below 10764 plants $\cdot$ ha^{-1} the detection model can count mature pumpkins at the same accuracy as manual counting.

Measuring Pumpkins

Along with counting targets, the detection model has the ability to estimate the area and diameter of each detected target. The Solvi diameter is defined as the longest distance across a target. The UAV image measured diameter was compared to the longest ground truth pumpkin dimension, whether length or diameter, to assess the accuracy of this feature. Fruit diameter was chosen over fruit area since it is a direct measured comparison. Diameter was measured to the closest centimeter. This evaluation was completed on discretely detected mature fruit. There were 27 detected ground truth fruits eliminated from this analysis since the detection model identified two adjacent pumpkin fruits as a single target. Since these groupings include a false negative, it would not give a factual representation of the measuring capabilities of a true positive pumpkin. If these data were included, the accuracy in measuring diameter would decrease. Accurate fruit measurement is dependent on accurate fruit detection and measuring

targets can only be initiated once fruit detection is highly accurate. The detection model identified 977 true positive pumpkins which were measured for accuracy in fruit diameter. All data were analyzed together across treatments and years.

Detected fruit diameter and ground truth fruit diameter were different ($p<0.001$). The model's mean diameter was 1.1 cm larger than the ground truth measured diameter. In general, the detection model overestimated the diameter. There were 170 fruits where there was no difference between methods. The model measured 43% of the fruit within 1 cm of the ground truth fruit diameter and 67% within 2 cm of ground truth fruit diameter.

There are several examples where the model grossly overestimated or underestimated the fruit diameter (Figure 3.3). These examples comprise only a small portion of the data and are highlighted to show potential areas of improvement for the model. Most underestimations were caused by fruit that is green yet was classified as mature enough to ripen off the vine and therefore was included in the data set. The green color may have made the target boundaries difficult to detect against foliage, distorting the outline of the target and causing the underestimation. The overestimations occurred when a leaf overlaid on the fruit and was perceived as part of the pumpkin. This inclusion of the leaf enlarged the target area, overestimating the fruit diameter.

The Bland-Altman analysis shows that the difference in diameter measurements between methods does not change as the diameter measurement changes (Figure 3.4). There difference distribution between methods stays the same throughout the fruit diameter range, showing homoscedasticity. This implies that there is no systematic error, and the model is equally accurate at measuring small diameters as it is at measuring large diameters. Errors that occur originate from the raster image and not from the detection model. From this analysis, 26 data

point were above and six data points below the 95% confidence interval, further confirming that the model overestimates fruit diameter.

Pumpkins are commercially sorted by fruit size and classified into corresponding bin categories of *Medium, Large, Extra-Large,* and *Jumbo*. Growers benefit from knowing the fruit size ahead of harvest to predict the bin categories and quantities of each category they can supply to their market. To understand the error in bin packing prediction, the fruit sizes of ground truth and the model were compared in terms of the bin categories (Table 3.4). The largest error occurred in the *Medium* bin category pumpkins were the model had a 52% error rate. There were only 93 fruit that were ground truth *Medium* pumpkins, which is a smaller sample size compared to the other fruit size categories. The detection model had a 28% and 29% error rate for *Large* and *Jumbo* bins respectively. *Extra-Large* bins had a 1% error rate. With these lower error rates, growers can predict pumpkin yield in terms of both bin quantity and bin category. The overall distribution of pumpkin diameter may be a contributing factor to the varying error rate of fruit bin size categorization.

Conclusion

Yield estimation is an imperative metric for growers to properly market their crop and prepare for harvest. Current commercial resources in UAVs and detection models predict pumpkin fruit number with a precision value of 0.90 to 1.0, recall 0.86 to 1.0, and F1 score 0.92 to 1.0. Overall accuracy for detecting fruit was 99% with error rate of 1%. The detection model generally overestimates pumpkin diameter, but 43% of fruit measured were within 1 cm of ground truth measurements.

A limitation of this study is that the unique identifying labels may have contributed to the detection model criteria. To further scrutinize UAV image yield estimation, this study could be

repeated without using white labels as unique identifiers. Another limitation is that the accuracy of the yield prediction decreases at a plant density of 10764 plants · ha^{-1}. Future research could analyze how additional image analysis can effectively correct false negative adjacent pumpkins which is a result of high plant density.

The benefit of UAV images and model detection software is the ability to count fruit and predict yield with aerial images and machine learning. This technology is faster than hand counting and is becoming more affordable for to use in agricultural settings. North Carolina pumpkin growers can use detection models like Solvi Plant AI to estimate fruit count with a high level of accuracy to prepare for harvest and predict in season yield counts.

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Table 3.1. Precision, recall, and F1 scores for ‘Kratos’ pumpkin fruit detection from UAV images and Solvi detection model.

2020							2021						
Plot	TP	FP	FN	P	R	F1	Plot	TP	FP	FN	P	R	F1
101	38	0	3	1.00	0.93	0.96	101	36	4	1	0.90	0.97	0.94
102	24	0	0	1.00	1.00	1.00	102	21	0	0	1.00	1.00	1.00
103	15	0	0	1.00	1.00	1.00	103	21	0	0	1.00	1.00	1.00
104	11	0	0	1.00	1.00	1.00	104	19	0	0	1.00	1.00	1.00
105	23	0	1	1.00	0.96	0.98	105	20	0	1	1.00	0.95	0.98
106	17	0	0	1.00	1.00	1.00	106	15	0	0	1.00	1.00	1.00
107	11	0	0	1.00	1.00	1.00	107	9	0	0	1.00	1.00	1.00
108	10	0	0	1.00	1.00	1.00	108	8	0	0	1.00	1.00	1.00
201	12	0	0	1.00	1.00	1.00	201	15	0	0	1.00	1.00	1.00
202	39	0	1	1.00	0.98	0.99	202	38	3	0	0.93	1.00	0.96
203	15	0	0	1.00	1.00	1.00	203	11	0	0	1.00	1.00	1.00
204	23	0	0	1.00	1.00	1.00	204	27	0	1	1.00	0.96	0.98
205	9	0	0	1.00	1.00	1.00	205	7	0	0	1.00	1.00	1.00
206	15	0	0	1.00	1.00	1.00	206	18	0	0	1.00	1.00	1.00
207	22	0	1	1.00	0.96	0.98	207	12	0	0	1.00	1.00	1.00
208	10	1	0	0.91	1.00	0.95	208	11	0	0	1.00	1.00	1.00
301	13	0	0	1.00	1.00	1.00	301	17	0	0	1.00	1.00	1.00
302	15	0	0	1.00	1.00	1.00	302	18	0	0	1.00	1.00	1.00
303	23	0	0	1.00	1.00	1.00	303	20	1	0	0.95	1.00	0.98
304	42	0	0	1.00	1.00	1.00	304	30	1	1	0.97	0.97	0.97
305	13	0	0	1.00	1.00	1.00	305	8	0	0	1.00	1.00	1.00
306	28	0	3	1.00	0.90	0.95	306	12	0	0	1.00	1.00	1.00
307	6	0	1	1.00	0.86	0.92	307	9	0	0	1.00	1.00	1.00
308	16	0	0	1.00	1.00	1.00	308	14	0	0	1.00	1.00	1.00
Mean				0.996	0.982	0.989	401	19	2	0	0.90	1.00	0.95
							402	20	0	0	1.00	1.00	1.00
TP = true positive							403	33	0	1	1.00	0.97	0.99
FP = false positive							404	18	0	0	1.00	1.00	1.00
FN= false negative							405	14	0	0	1.00	1.00	1.00
P= precision							406	18	0	1	1.00	0.95	0.97
R= Recall							407	8	0	0	1.00	1.00	1.00
F1 = F1 score.							408	9	1	0	0.90	1.00	0.95
							Mean				0.989	0.992	0.989
							Overall				0.990	0.988	0.988

Table 3.2. Ground truth ‘Kratos’ pumpkins count per plot compared to UAV images and Solvi object detection model.

Year 2020				
Plot	Ground Truth	Solvi TPs	Accuracy	Error (%)
101*	40	38	0.95	0.05
102	24	24	1.00	0.00
103	15	15	1.00	0.00
104	11	11	1.00	0.00
105*	24	23	0.96	0.04
106	17	17	1.00	0.00
107	11	11	1.00	0.00
108	10	10	1.00	0.00
201	12	12	1.00	0.00
202*	40	39	0.97	0.03
203	15	15	1.00	0.00
204	23	23	1.00	0.00
205	9	9	1.00	0.00
206*	15	15	1.00	0.00
207	23	22	0.96	0.04
208	10	10	1.00	0.00
301	13	13	1.00	0.00
302	15	15	1.00	0.00
303	23	23	1.00	0.00
304*	42	42	1.00	0.00
305	13	13	1.00	0.00
306*	31	28	0.90	0.10
307	7	6	0.86	0.14
308	16	16	1.00	0.00
Mean			0.98	0.017

Solvi TP = True Positive pumpkins detected by Solvi

*plots with plant density of 10,764 plants · ha^{-1}

Year 2021				
Plot	Ground Truth	Solvi TPs	Accuracy	Error (%)
101*	37	36	0.97	0.03
102	21	21	1.00	0.00
103	21	21	1.00	0.00
104	19	19	1.00	0.00
105*	21	20	0.95	0.05
106	15	15	1.00	0.00
107	9	9	1.00	0.00
108	8	8	1.00	0.00
201	15	15	1.00	0.00
202*	38	38	1.00	0.00
203	11	11	1.00	0.00
204	28	27	0.96	0.04
205	7	7	1.00	0.00
206	18	18	1.00	0.00
207*	12	12	1.00	0.00
208	11	11	1.00	0.00
301	17	17	1.00	0.00
302	18	18	1.00	0.00
303	20	20	1.00	0.00
304*	32	30	0.94	0.06
305	8	8	1.00	0.00
306*	12	12	1.00	0.00
307	9	9	1.00	0.00
308	14	14	1.00	0.00
401	19	19	1.00	0.00
402	20	20	1.00	0.00
403*	34	33	0.97	0.03
404	18	18	1.00	0.00
405	14	14	1.00	0.00
406*	19	18	0.95	0.05
407	8	8	1.00	0.00
408	9	9	1.00	0.00
Mean			0.99	0.008
Overall			0.99	0.011

Table 3.3. Mean ‘Kratos’ pumpkin diameter per plot in cm for ground truth data compared to UAV images and Solvi detection model.

2020		
Plot	Ground Truth	Solvi
101	28.6	28.7
102	31.2	31.9
103	33.5	33.5
104	36.1	36.6
105	29.6	30.2
106	31.6	32.2
107	34.9	33.5
108	33.5	34.0
201	35.2	35.3
202	29.1	29.8
203	33.3	34.1
204	31.9	32.5
205	37.0	36.1
206	31.9	31.4
207	29.4	29.0
208	35.3	35.2
301	34.5	34.9
302	31.1	32.1
303	33.7	33.5
304	28.4	28.9
305	35.0	33.7
306	29.4	29.2
307	37.8	36.8
308	32.8	32.2

2021		
Plot	Ground Truth	Solvi
101	29.2	31.6
102	32.3	34.1
103	32.8	35.7
104	34.3	36.1
105	30.6	30.9
106	31.6	33.5
107	34.4	36.6
108	36.3	37.6
201	34.7	37.3
202	28.3	31.2
203	35.7	37.8
204	32.5	34.8
205	39.2	38.3
206	31.9	34.0
207	31.2	31.8
208	33.5	35.5
301	34.4	37.0
302	34.5	36.2
303	33.4	34.2
304	28.6	30.8
305	36.3	36.5
306	31.0	33.6
307	34.2	36.6
308	32.7	35.1
401	33.5	35.7
402	33.3	34.3
403	29.4	32.1
404	34.7	36.2
405	32.9	34.8
406	30.1	32.2
407	35.9	35.1
408	34.4	35.9

Table 3.4. Fruit count for the different fruit size bin categories by ground truth and UAV images and Solvi detection model.

Bin Category	Fruit Diameter Range (cm)	Method		Percent Error
		Ground Truth	Solvi	
	<23	1	6	
Medium	23-26	93	45	52%
Large	27-30	269	192	29%
Extra-Large	30-34	347	351	1%
Jumbo	35-36	148	189	28%
	>36	119	194	

Figure 3.1. Images of false positives from UAV images and Solvi detection model for mature ‘Kratos’ pumpkin fruit.

Figure 3.2. Images of false negatives from UAV images and Solvi detection model for mature ‘Kratos’ pumpkin fruit.

Figure 3.3. Examples of largest diameter overestimations and underestimation from UAV images Solvi detection model for mature ‘Kratos’ pumpkin fruit.

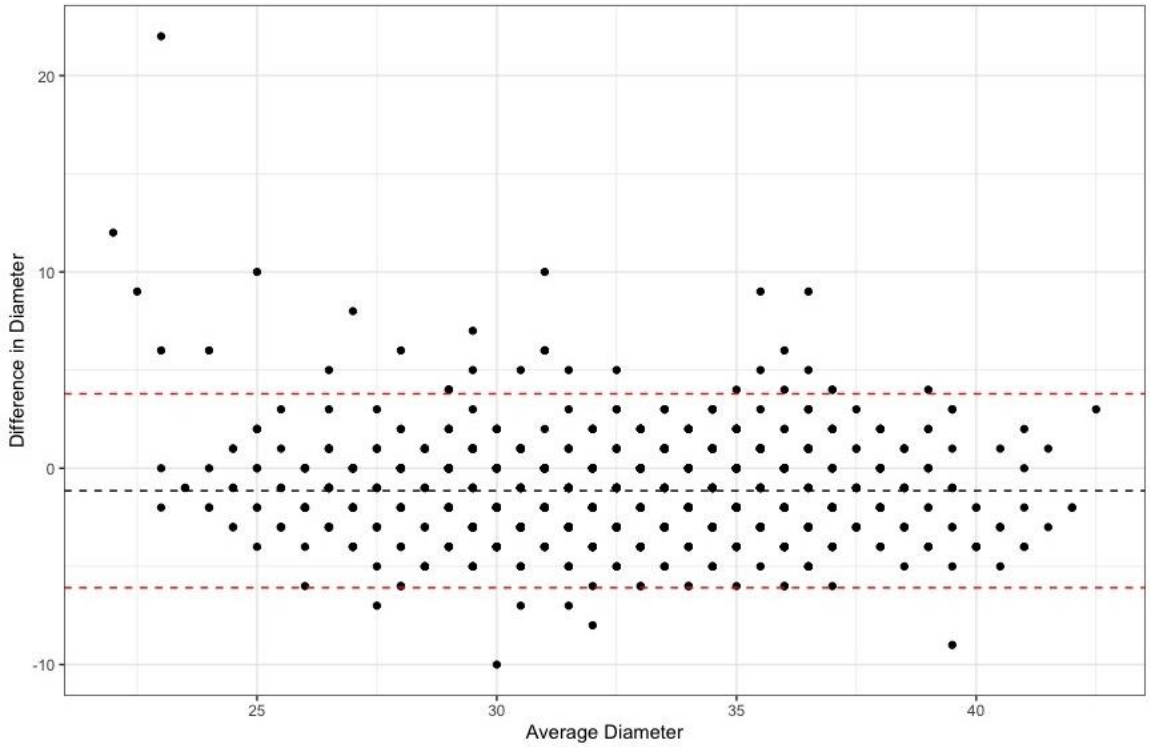

Figure 3.4. Bland Altman plot of ‘Kratos’ pumpkin diameter measured by ground truth versus UAV images and Solvi detection model.
Note: Red dashed lines mark the 95 % confidence interval.

APPENDICES

Appendix A: Pumpkin (*Cucubita sp.)* spray schedule for 2020 and 2021 for production study located at Upper Mountain Research Station, Laurel Springs, NC.

Table A.1 2020 Pumpkin (*Cucubita sp.)* production spray schedule for Upper Mountain Research Station, Laurel Springs, NC.

Date	Chemical	Rate of Product	Units
4/3/20	Roundup Power Max Herbicide 524-549 Glyphosate 4 hrs	27	ounces per acre
6/26/20	Command 3ME Herbicide 279-3158 Clomazone 12	16	ounces per acre
	Dual Magnum Herbicide 100-816 S-Metolachlor 24	20	ounces per acre
	Reflex Herbicide 100-993 Sodium salt of fomesafen 24	16	ounces per acre
6/26/20	Sandea Herbicide 81880-18-10163 Halosulfuron-methyl 12	0.75	ounces per acre
7/9/20	Venom Insecticide 59639-135 Dinotefuran 12	4	ounces per acre
8/1/20	Initiate 720 Flowable Fungicide 34704-881 Chlorothalonil 12	32	ounces per acre
	Rampart Fungicide 34704-924 mono- and dipotassium salts of Phosphorous acid 4	48	ounces per acre
8/8/20	Initiate 720 Flowable Fungicide 34704-881 Chlorothalonil 12	24	ounces per acre
	Quadris Fungicide 100-1098 Azoxystrobin 4	14	ounces per acre
	Quintec Fungicide 62719-375 Quinoxyfen 12	6	ounces per acre
8/8/20	Rampart Fungicide 34704-924 mono- and dipotassium salts of Phosphorous acid 4	2	quarts per acre
8/16/22	Initiate 720 Flowable Fungicide 34704-881 Chlorothalonil 12	24	ounces per acre
	Initiate 720 Flowable Fungicide 34704-881 Chlorothalonil 12	24	ounces per acre
	Rampart Fungicide 34704-924 mono- and dipotassium salts of Phosphorous acid 4	2	quarts per acre
8/16/20	Precision Spreader Surfactant N/A alkylpolyoxethylene, glycol derivatives, humectant and formulation aids 0	32	32 oz per 100 gal
8/25/20	Initiate 720 Flowable Fungicide 34704-881 Chlorothalonil 12	24	ounces per acre
	Quadris Fungicide 100-1098 Azoxystrobin 4	15.5	ounces per acre
	Torino Fungicide 8033-103-10163 cyflufenamid 4	3.4	ounces per acre

8/25/20	Precision Spreader Surfactant N/A alkylpolyoxethylene, glycol derivatives, humectant and formulation aids 0	32	32 oz per 100 gal
8/28/20	Roundup Power Max Herbicide 524-549 Glyphosate 4	1	quarts per acre
8/31/20	Orondis opti A Fungicide 100-1572 Oxathiapiprolin 4	4	ounces per acre
	Champion WP Fungicide 55146-64 Copper hydroxide 24	2	pounds per acre
	Roper DF Rainshield Fungicide 34704-1063 Mancozeb 24	3	pounds per acre
8/31/20	Liberate Surfactant EXEMPT Lecithin, methyl esthers of fatty acids, and alcohol ethoxylate 0	32	32 oz per 100 gallons
	Quadris Fungicide 100-1098 Azoxystrobin 4	15.5	ounces per acre
8/7/20	Roper DF Rainshield Fungicide 34704-1063 Mancozeb 24	3	pounds per acre
	Liberate Surfactant EXEMPT Lecithin, methyl esthers of fatty acids, and alcohol ethoxylate 0	32	32 oz per 100 gal
	Torino Fungicide 8033-103-10163 cyflufenamid 4	3.4	ounces per acre
9/7/20	Rampart Fungicide 34704-924 mono- and dipotassium salts of Phosphorous acid 4	2	quarts per acre
9/10/20	Initiate 720 Flowable Fungicide 34704-881 Chlorothalonil 12	24	ounces per acre
9/10/20	Ranman Fungicide 71512-3-279 Cyazofamid 12	2.75	ounces per acre
	Liberate Surfactant EXEMPT Lecithin, methyl esthers of fatty acids, and alcohol ethoxylate 0	32	32 oz per 100 gallons
	Pristine Fungicide 7969-199 Pyraclostrobin 12	16	ounces per acre
9/21/20	Liberate Surfactant EXEMPT Lecithin, methyl esthers of fatty acids, and alcohol ethoxylate 0	32	32 oz per 100 gallons of water
	Roper DF Rainshield Fungicide 34704-1063 Mancozeb 24	3	pounds per acre
	Microthial Disperss Fungicide 70506-187 Sulfur 24	4	pounds per acre
9/26/20	Cuprofix Ultra 40 Fungicide 70506-201 Copper sulfate 48	2	pounds per acre
	Microthial Disperss Fungicide 70506-187 Sulfur 24	2	pounds per acre
	Liberate Surfactant EXEMPT Lecithin, methyl esthers of fatty acids, and alcohol ethoxylate 0	32	32 oz per 100 gallons

Table A.2.2021 Pumpkin (*Cucubita sp.)* production spray schedule for Upper Mountain Research Station, Laurel Springs, NC.

Date	Chemical	Rate of Product	Units
4/7/21	Roundup Power Max Herbicide 524-549 Glyphosate 4	27	ounces per acre
5/14/21	Roundup Power Max Herbicide 524-549 Glyphosate 4	1.5	quarts per acre
6/19/21	Command 3ME Herbicide 279-3158 Clomazone 12	16	ounces per acre
	Dual Magnum Herbicide 100-816 S-Metolachlor 24	20	ounces per acre
	Reflex Herbicide 100-993 Sodium salt of fomesafen 24	16	ounces per acre
6/19/21	Sandea Herbicide 81880-18-10163 Halosulfuron-methyl 12	0.75	ounces per acre
6/23/21	Command 3ME Herbicide 279-3158 Clomazone 12	16	ounces per acre
	Dual Magnum Herbicide 100-816 S-Metolachlor 24	20	ounces per acre
	Reflex Herbicide 100-993 Sodium salt of fomesafen 24	16	ounces per acre
7/9/21	Admire Pro Insecticide 264-827 Imidacloprid 12	10	ounces per acre
7/22/21	Roundup Power Max Herbicide 524-549 Glyphosate 4	32	ounces per acre
7/30/21	Initiate 720 Flowable Fungicide 34704-881 Chlorothalonil 12	2	pints per acre
	Sivanto Insecticide 264-1141 Flupyradifurone 4	14	ounces per acre
	Quintec Fungicide 62719-375 Quinoxyfen 12	4	ounces per acre
7/30/21	Rampart Fungicide 34704-924 mono- and dipotassium salts of Phosphorous acid 4	1	quarts per acre
8/6/21	Orondis opti A Fungicide 100-1572 Oxathiapiprolin 4	3	ounces per acre
	Orondis opti B Fungicide 50534-188-100 Chlorothalonil 12	96	ounces per acre
8/13/21	Roundup Power Max Herbicide 524-549 Glyphosate 4	32	ounces per acre
8/13/21	Topsin-M WSB Fungicide 7345-16-70506 Thiophanate-methyl 24	0.5	pounds per acre
	Orondis opti B Fungicide 50534-188-100 Chlorothalonil 12	32	ounces per acre
8/21/21	Assail 30SG Insecticide 8033-36-70506 acetamiprid 12	5.3	ounces per acre
	Ranman Fungicide 71512-3-279 Cyazofamid 12	2.75	ounces per acre
	Liberate Surfactant EXEMPT Lecithin, methyl esthers of fatty acids, and alcohol ethoxylate 0		16 oz per 100 gallons

8/21/21	Torino Fungicide 8033-103-10163 cyflufenamid 4	3.4	ounces per acre
8/27/21	Plantskydd deer repellent	2.2	pounds per acre
8/28/21	Liberate Surfactant EXEMPT Lecithin, methyl esthers of fatty acids, and alcohol ethoxylate 0	16	16 oz per 100 gallons
	Roper DF Rainshield Fungicide 34704-1063 Mancozeb 24	2	pounds per acre
	Monsoon Fungicide 34704-900 Tebuconazole 12	8	ounces per acre
8/30/21	Roundup Power Max Herbicide 524-549 Glyphosate 4	32	ounces per acre
9/6/21	Torino Fungicide 8033-103-10163 cyflufenamid 4	3.4	ounces per acre
	Orondis opti A Fungicide 100-1572 Oxathiapiprolin 4	2	ounces per acre
	Liberate Surfactant EXEMPT Lecithin, methyl esthers of fatty acids, and alcohol ethoxylate 0		20 oz per 100 gallons
9/6/21	Roper DF Rainshield Fungicide 34704-1063 Mancozeb 24	2	pounds per acre
9/13/21	Microthial Disperss Fungicide 70506-187 Sulfur 24	2	pounds per acre
	Roper DF Rainshield Fungicide 34704-1063 Mancozeb 24	3	pounds per acre
	Liberate Surfactant EXEMPT Lecithin, methyl esthers of fatty acids, and alcohol ethoxylate 0		20 oz per 100 gallons
9/16/21	Cuprofix Ultra 40 Fungicide 70506-201 Copper sulfate 48	2	pounds per acre
	Cuprofix Ultra 40 Fungicide 70506-201 Copper sulfate 48	2	pounds per acre
9/17/21	Roundup Power Max Herbicide 524-549 Glyphosate 4	32	ounces per acre

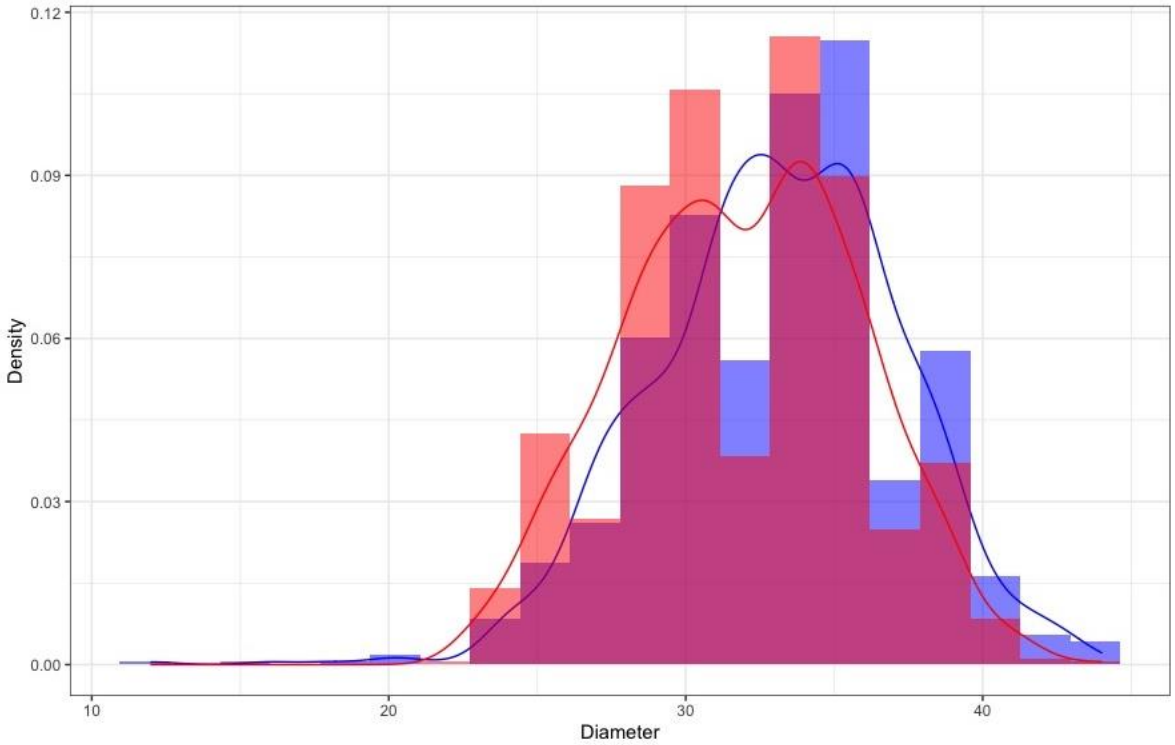

Figure A.1. Distribution for ‘Kratos’ pumpkin diameter measured by ground truth versus UAV images and Solvi detection model.
Note: Red graphics indicate ground truth, blue graphics indicate Solvi object detection software