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High-density Planting and a Smaller Row Width Increased Yield and Decreased Fruit Size of Pumpkins

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Abstract. **Pumpkins (*Cucurbita* sp.) grown in North Carolina are a nascent specialty crop that has only risen to a national production level in the past 10 years. There are only general cultural management guidelines for this region, resulting in variation in plant density and inefficient production. Production field studies of the cultivar Kratos were conducted 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 10,764 plants per hectare with row widths of 1.5 and 3.0 m were grown in 2020 and 2021 in North Carolina. Data regarding fruit size, fruit size variance, and yield per area were collected. 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. The fruit number per hectare and fruit weight per hectare increased as plant density increased, with the highest production at 10,764 plants per hectare. For years combined, reducing the row width from 3.0 to 1.5 m increased the fruit weight and diameter, but not the 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 10,764 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.**

There is a growing demand for pumpkins (*Cucurbita* sp.) in the United States because of the increase in ornamental use and seasonal agrotourism among consumers (USDA ERS 2015). Commercial production within the United States has climbed from 662.3 million kg in 2000 to 687.6 million kg in 2010, and to 991.6 million kg in 2021 (USDA ESMIS 2022). Pumpkins are primarily used for food processing and seasonal decoration and include traditional carving pumpkins and specialty pumpkins. Interest in specialty pumpkins continues to grow among consumers in the United States (USDA ERS 2022).

Pumpkins are an emerging crop in North Carolina, with the first national production records reported in 2016 (USDA NASS 2018). Pumpkins serve as a supplemental crop for commercial growers in North Carolina, where most plant between 0.4 and 2 ha to provide additional income for their larger staple crops (North Carolina Department of Agriculture and Consumer Services 2023). Most large acreage of pumpkins is grown in the western mountain region, which has a cooler plant zone (6a) compared with the rest of the state. In 2021, North Carolina produced 13.3 million kg of pumpkins over 1498 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 United States. 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 that articulate the same attribute. Plant density specifies the plant quantity in the context of plants per hectare, whereas plant spacing specifies the area that each plant occupies. The plant spacing recommendation for the southeastern region of the United States ranges from 1.7 m^2 to 2.8 m^2 for semi-vine growth habit pumpkins, thus equating to 5883 and 3571 plants/ha, respectively (Kemble et al. 2022). North Carolina does not have state-specific plant spacing recommendations for commercial pumpkins. If clear guidelines existed, then growers could potentially grow pumpkins more efficiently. On average, North Carolina has a lower yield per area compared with other states (USDA NASS 2022). North Carolina has produced 8850 $kg \cdot ha^{-1}$; however, Illinois, which is the top-producing state, has produced 45,932 $kg \cdot ha^{-1}$, and other states such as New York and Virginia have yielded 16,805 and 19,494 $kg \cdot ha^{-1}$ 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 that influences fruit yield. There is an ideal plant density for every crop at which 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 a higher fruit number per area (Wehner et al. 2020). During a study performed in New York, the vine-type growth habit pumpkin, ‘Howden’, and semi-vine growth habit pumpkin, ‘Wizard’, experienced an increase in fruit number and total weight per hectare by increasing the density from 2290 to 8690 plants/ha (Reiners and Riggs 1999). A study performed in Egypt also resulted in increased fruit total weight per hectare with vine-type ‘Dickinson’ by increasing the density from 4780 to 9560 plants/ha (El-Sayed et al. 2011). Another study performed in northern Mississippi tested plant density to establish a recommendation for the 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/ha, 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 the results of other studies that reported an increase in fruit number and total weight as plant density increased. The authors of the Cushman study attributed this contrary outcome to testing densities that were too low to realize 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 (Reiners and Riggs 1999). For these cultivars, the average fruit weight was reduced from 9.6 to 8.9 kg at one study location and from 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 density changed from 4780 to 9560 plants/ha (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 high variability in fruit size, then more fruit will be below or above the standardized size, creating product waste, inefficiency in harvesting, or 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 that this study aimed to fill.

Plant density is controlled based on the plant area, 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 the in-row distance to accommodate field equipment for crop maintenance. The shape of the plant area, which is dictated by the relationship between row width and in-row measurements, affects the crop yield. When the spacing dimensions are equidistant, crops have a higher yield because a square shape, compared with a rectangular shape, reduces plant-to-plant competition (Pant 1979). Row width recommendations for pumpkins in the Southeast is 1.8 to 2.4 m, whereas the 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, and plant areas from 0.5 to 6.7 m^2 have been assessed (Cushman et al. 2004; El-Sayed et al. 2011; Reiners and Riggs 1997). One previous pumpkin study specifically examined reducing the row width while maintaining the same plant density. This study had three plant areas, 1.1, 2.2, and 3.2 m^2, which are equivalent to plant densities of 2290, 4480, and 8960 plants/ha, respectively, at two different row widths of 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). Because only three plant densities have been studied, there is a gap in the literature regarding 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 this research was to provide plant density guidelines for commercial pumpkin production in North Carolina.

Materials and Methods

This research was conducted at the North Carolina Department of Agriculture and Consumer Services Upper Mountain Research Station in Laurel Springs, NC (lat. 36.398789°N, long. 81.307266°W). The field site had a Toxaway loamy soil type (USDA NRCS 2022) and was sown during the previous fall with an annual rye cover crop. A burndown herbicide (Appendix A1) was used to kill the cover crop in the spring. A 2-week period was allowed before applying pre-plant fertilizer, discing, and rototilling the field. Two pre-plant fertilizers were applied, 112 $kg \cdot ha^{-1}$ of 0N–0P–50K and 329.3 $kg \cdot ha^{-1}$ of 17N–17P–17K. Thirty-five days after planting, plots were side-dressed with 39.2 $kg \cdot ha^{-1}$ of 15N–15P–15K. 'Kratos' (*Cucurbita pepo*) (HM Clause, Davis, CA, USA), which is characterized by the company's cultivar description as a 9- to 13-kg large carving pumpkin with a semi-vine growth pattern, was chosen for this study because it is the most popular cultivar for growers in the United States (Froese J, personal communication). Four plant densities, 10,764, 5382, 3588, and 2691 plants/ha, which are equivalent to plant areas of 0.9, 1.9, 2.8, and 3.7 m^2, respectively, were tested (Table 1). All 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, whereas 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 created using a randomized complete block design with three replications in 2020 and four replications in 2021. Each plot had four rows measuring 12.2 m in length.

Seeds were planted using a crow hop similar to the "Easy-Plant Jab Type" planter (Johnny's Selected Seeds, Winslow, ME, USA), which presses seeds into the ground and lightly covers them. Sowing occurred on 5 Jun 2020 and 17 Jun 2021. Two seeds per hill were planted 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 stands. 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 A1) was implemented just before blooming with protectant sprays that continued every 7 to 14 d until harvest based on rainfall between sprayings. The primary diseases of concern were Plectosporium blight (*Plectosporium tabacinum*), cucurbit powdery mildew (*Pseudoperonospora cubensis*), and cucurbit downy mildew (*Podosphaera xanthii* and *Erysiphe cichoracearum*). When 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 or needed.

A one-time harvest occurred 1 Oct 2020 and 23 Sep 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 × 6.1 m, with a total area of 37.2 m^2. The harvest area for the 1.5-m row width spacings measured 6.1 × 3.0 m, with a total area of 18.6 m^2. Data of marketable pumpkins regarding weight, diameter, length, and fruit number per plot were collected.

Table 1. Summary of row width, in-row spacing, and plant area for the corresponding plant density for pumpkin (*Cucurbita pepo*) spacing trials.

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

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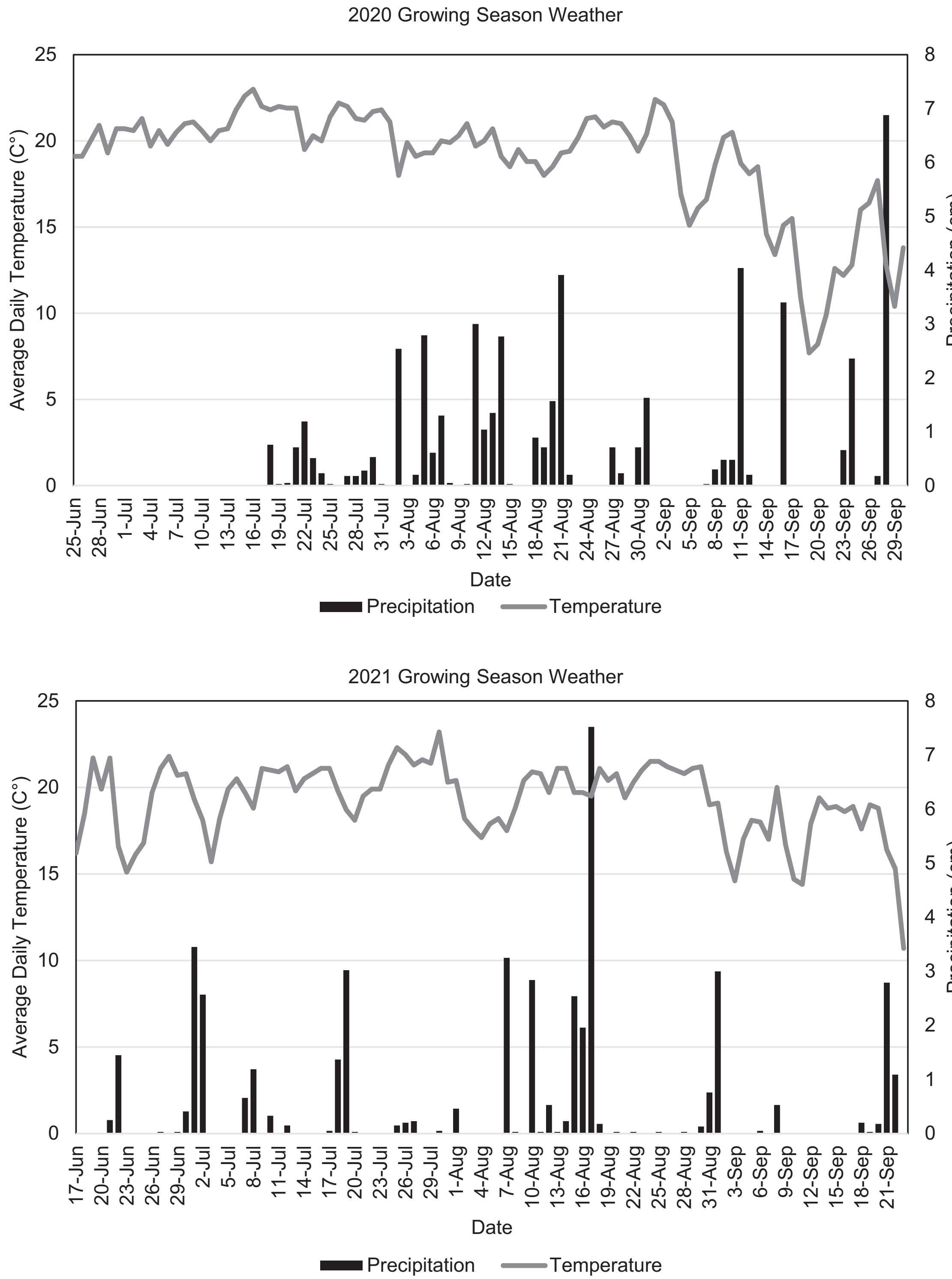

Fig. 1. Growing season average daily temperature and total daily precipitation for Laurel Springs, NC, in 2020 and 2021.

Length was the distance between the stem and 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 were close to maturity. The marketable green pumpkins were mostly green but had orange ground spots or an orange background, which indicated the ability to turn orange off of the vine. Rotten, immature, or severely blemished fruit were not included.

In 2020, the average daily high temperature was 24.0 °C, and the average low temperature was 14.5 °C, with 50.0 cm of total precipitation during the growing season (Fig. 1) (North Carolina Department of Agriculture and Consumer Services 2022). In 2021, the average high and low temperatures 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.

An analysis of variance was completed to test the significance of plant density and row width to yield components. A linear regression analysis was used to quantify how much these variables predict each other. The statistical analysis was completed using SAS GLM and Mixed Procedures (SAS version 9.4; SAS Institute Inc., Cary, NC, USA). Raw data were transformed to include yield per hectare measurements.

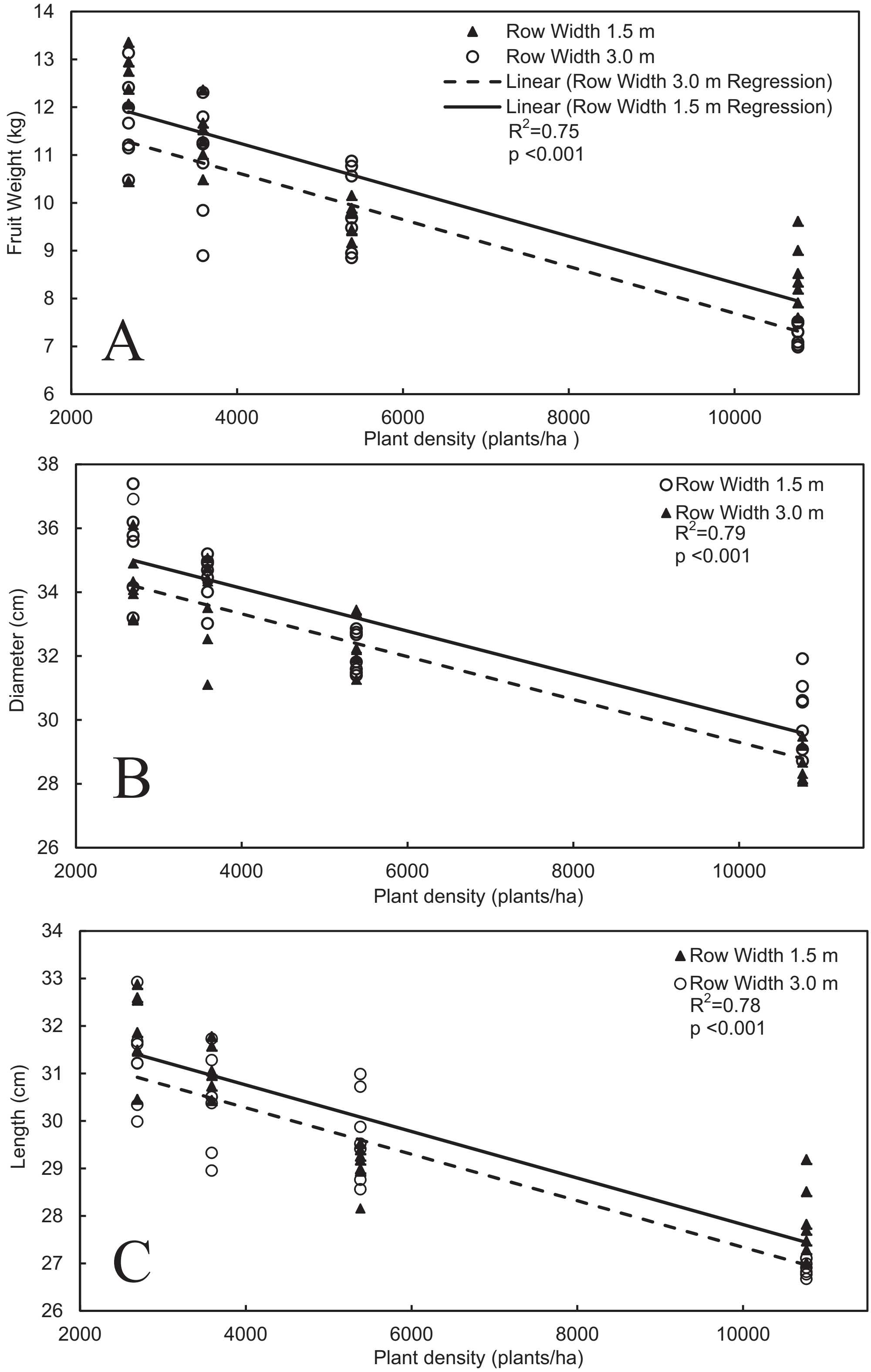

Fig. 2. Fruit size yield components for 'Kratos' pumpkins grown at plant densities of 2691, 3588, 5382, and 10,764 plants/ha with row widths of 1.5 and 3.0 m. These components were analyzed as combined years with no year × population interaction. (**A**) $R^2 = 0.75$, $P < 0.001$; 1.5-m row width: $y = 13.22 + (-0.00049x)$; 3.0-m row width: $y = 12.59 + (-0.00049x)$. (**B**) $R^2 = 0.79$; $P < 0.001$; 1.5-m row width: $y = 36.82 + (-0.00067x)$; 3.0-m row width: $y = 36.0 + (-0.00067x)$. (**C**) $R^2 = 0.78$, $P < 0.001$; 1.5-m row width: $y = 32.72 + (-0.00049x)$; 3.0-m row width: $y = 32.24 + (-0.00049x)$.

Results and Discussion

There was a year × 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 37.2 m^2 and 18.6 m^2 plot areas to a hectare. There were no year × treatment interactions for fruit weight ($P = 0.090$), 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 (Fig. 2A). A

Table 2. Analysis of variance for pumpkin (*Cucurbita pepo*) fruit weight, diameter, and length for row widths and plant densities analyzed as combined years.

	Fruit measurement		
Treatment	Wt (kg)	Diam (cm)	Length (cm)
Row width (m)			
1.5	10.5 a	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[i]	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[i]	1.1	1.3	0.9
Row width × density			
Significance	0.299	0.124	0.106

[i] Tukey's honestly significant difference values within each column for each variable at $P \leq 0.05$.

density of 2691 plants/ha had a mean fruit weight of 12.0 kg compared with a density of 10,764 plants/ha, which had a mean fruit weight of 7.9 kg (Table 2). Plant densities had different fruit weights, except for 3588 and 2691 plants/ha, which did not have different fruit weights. The reduction in fruit weight aligns with the results of previous pumpkin studies that reported that fruit weight decreased for different growth habit cultivars when plant density increased (El-Sayed 2011; Reiners and Riggs 1997). This was also true in terms of 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).

Row width had an effect on fruit weight ($P = 0.027$) (Table 2). The mean fruit weight for the 1.5-m row width was 10.5 kg compared with the 3.0-m row width, with fruit weight of 9.9 kg. The 1.5-m row width may have produced larger fruit because of the more equidistant growing area compared with 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 by using a smaller row width, creating a more equidistant planting area. Our results are contrary to those of another row width study during which decreasing the row width spacing from 3.6 to 1.8 m had a negligible effect on fruit size for plant densities of 2290, 4480, and 9860 plants/ha (Reiners and Riggs 1999). Reiners and Riggs stated that the impact of row width spacing may become significant at higher plant densities.

Fruit diameter and length. Fruit diameter linearly decreased as plant density increased (Fig. 2B). Increasing the plant density from 2691 to 10,764 plants/ha decreased the fruit diameter from 34.9 to 29.4 cm (Table 2). Plant densities produced different fruit diameters, except for 2691 and 3588, which did not have different fruit diameters from one another. The row width had an effect on the fruit diameter ($P = 0.022$) (Table 2). The row width of 1.5 m had a fruit diameter of 33.1 cm compared with 3.0 m, which had a diameter of 32.2 cm.

Fruit length linearly decreased as plant density increased (Fig. 2C). The density of 2691 plants/ha had a fruit length of 31.6 cm compared with the density 10,764 plants/ha, which had a fruit length of 27.4 cm (Table 2). Similar to fruit weight and diameter, the plant densities of 2691 and 3588 did not have different fruit lengths from one another. The row width did not have an effect on fruit length ($P = 0.097$).

Many studies have reported that fruit size decreased with increased plant density; however, the exact relationship between diameter and length was previously unknown. In the 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. Mathematically, because volume is based on length and diameter, our results of decreased length and diameter are similar to those of Cushman regarding decreased fruit volume. Our study clarified how the individual metrics of diameter and length change with the reduction of overall fruit size. According to 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 (data not shown). A limitation of this study was 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 regarding 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 with a 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/ha with a 1.5-m row width.

Fruit uniformity. The uniformity of fruit size was not different across plant densities and row widths for both years ($P = 0.233$) (data not shown). Growing fruit with a consistent size benefits growers because 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. Because plant densities and row widths were not different, growers do not need to consider fruit uniformity when choosing the appropriate plant density for

Table 3. Analysis of variance for pumpkin (*Cucurbita pepo*) fruit number per hectare and kilogram per hectare for plant densities and row widths analyzed as separate years.

	Yr			
	2020		2021	
Treatment	No. fruit/ha	Yield (kg·ha^{-1})	No. fruit/ha	Yield (kg·ha^{-1})
Row width (m)				
1.5	8,342 a	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[i]	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

[i] Tukey's honestly significant difference values within each column for each variable at $P \leq 0.05$.

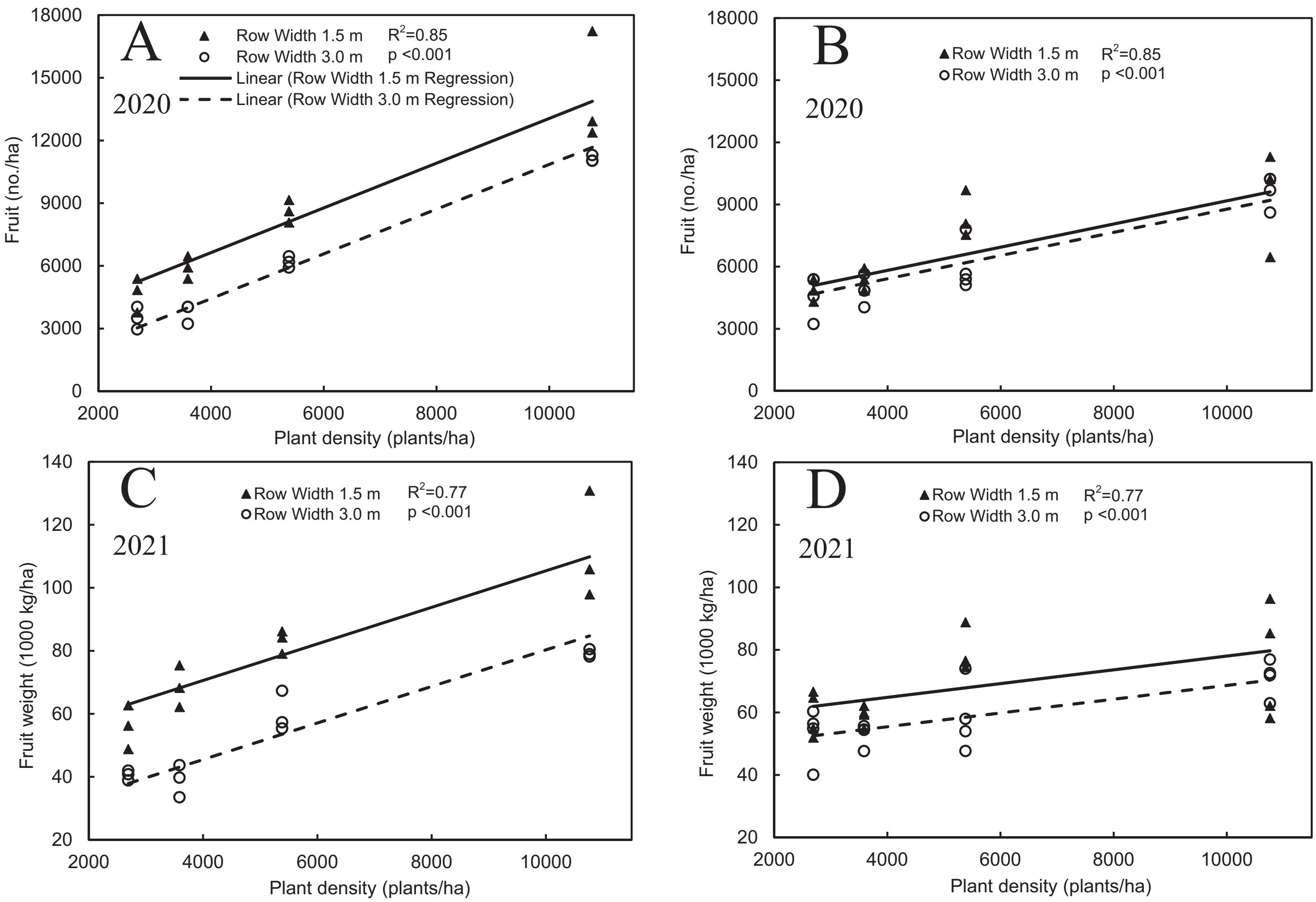

Fig. 3. Per area yield components for 'Kratos' pumpkins grown at plant densities of 2691, 3588, 5382, and 10,764 plants/ha with row widths of 1.5 and 3.0 m. These components were analyzed per year with a year × population interaction. (**A**) 2020: $R^2 = 0.85$, $P < 0.001$; 1.5-m row width: y = 2353 + 1.1x; 3.0-m row width: y = 156 + 1.1x. (**B**) 2021: $R^2 = 0.85$, $P < 0.001$; 1.5-m row width: y = 3580 + 0.6x; 3.0-m row width: y = 3177 + 0.6x. (**C**) 2020: $R^2 = 0.77$, $P < 0.001$; 1.5-m row width: y = 47,387 + 5.8x; 3.0-m row width: y = 22,296 + 5.8x. (**D**) 2021 $R^2 = 0.77$, $P < 0.001$; 1.5-m row width: y = 56,017 + 2.2x; 3.0-m row width: y = 46,625 + 2.2x.

their production. No previous studies have compared the fruit size uniformity based on plant density. 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 (Fig. 3A and B). In 2020, fruit number per hectare increased from 4081 to 12,648 fruit/ha as plant density increased from 2691 to 10,764 (Table 3). Similarly, in 2021, an increase from 4676 to 9149 fruit/ha with the same density increase occurred. 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 on a plot basis (Fig. 4). For both years, plant densities of 2691 and 3588 were not different for fruit number per hectare. Additionally, 10,764 plants/ha 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) performed two different studies and observed that pumpkin quantity per hectare increased with increased plant density. Watermelon studies showed similar results, with fruit quantities that 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 3). The 1.5-m row width had 8342 fruit/ha compared with 6144 for the 3.0-m row width, which is a difference of 36%. The results from 2020 assert that at the same plant density, pumpkin quantities increase with more equidistant plant area. Interplant spacing is important because plants respond to neighborhood densities (Weiner 1990). These results align with those of a study performed in New York that reported that at a high density of 8960 plants/ha, a 1.8-m row width produced more fruit per hectare compared with 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 in the 3.0-m row width (Table 3). The discrepancy of the effect of 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.

Increasing plant density increases the number of fruits that are produced, which could translate into greater profits depending on fruit sizes and the associated commercial bin sizes. However, increasing plant density also increases the associated seed cost. Growers should carefully identify which planting densities will lead to the highest profits based on their market needs and evaluate their ability to manage purchasing additional seeds. Heagy et al. (unpublished) reviewed the cost per plant density and profit per plant density of pumpkins.

Fruit yield: Kilograms per hectare. Total fruit weight per hectare is an effective way of measuring 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 (Fig. 3C and D). In 2020, increasing density from 2691 to 10,764 plants/ha increased yield 98%, from 48,227 to 95,365 $kg \cdot ha^{-1}$ (Table 3). In 2021, this same increase in plant density increased yield 30%, from 56,223 to 73,261 $kg \cdot ha^{-1}$. These results are aligned with previous pumpkin density studies in which fruit yield increased with increasing plant density (El-Sayed 2011; Reiners and Riggs 1999). This increase in yield occurs in other crops, such as watermelon

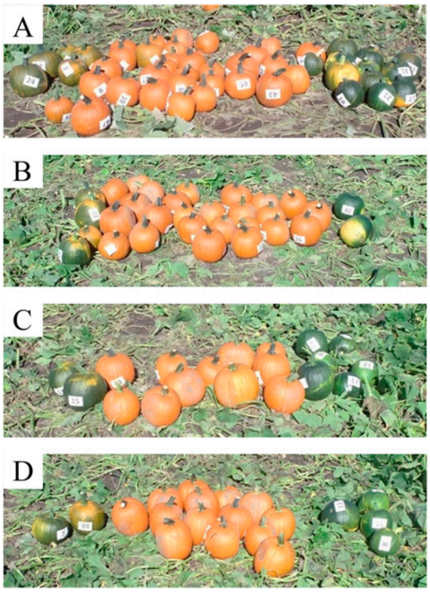

Fig. 4. Pumpkin yields from 37.2 m^2 research plots at varying plant densities with a 3.0-m row width: (**A**) 10,764 plants/ha; (**B**) 5382 plants/ha; (**C**) 3588 plants/ha; and (**D**) 2691 plants/ha.

and squash (Brinen et al. 1979; Dweikat and Kostewicz 1989; NeSmith 1993). However, a pumpkin study showed the opposite effect; fruit yield in kilograms per hectare decreased with increased density (Cushman et al. 2004). This result was attributed to testing lower plant densities for which the benefit of smaller plant areas was not captured by the data.

The 1.5-m row width had higher fruit yield compared with the 3.0-m row widths in 2020 ($P < 0.001$) and 2021 ($P = 0.010$) (Table 3). In 2020, the 1.5-m row width yielded 79,783 $kg \cdot ha^{-1}$ compared with the 3.0-m row width with 54,692 $kg \cdot ha^{-1}$. Similarly, in 2021, the 1.5-m row width yielded 68,241 $kg \cdot ha^{-1}$ compared with 58,849 $kg \cdot ha^{-1}$ from the 3.0-m row width. The outcome of this study indicated that total weight per hectare increases by decreasing the row width. The 1.5-m row width created a more equidistant growing area, thereby allowing the plants to be more productive through fruit yield (Pant 1979). Comparable to our results, those of the Reiners and Riggs (1999) study had higher fruit weight per hectare at a 1.8-m row width compared with a 3.6-m row width at a plant density of 8960 $kg \cdot ha^{-1}$.

Conclusion

This research specifies the effects of plant density and row width on yield for the pumpkin cultivar Kratos and provides plant spacing recommendations for growers. Our results validated 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. Conversely, fruit weight and fruit number per area increase up to the highest density of 10,764 plants/ha. During our study, pumpkins yielded the most fruit weight per hectare at 10,764 plants/ha with a 1.5-m row width. Regarding total weight per hectare and fruit size, a more equidistant area created by row width and in-row distances, produces a more prolific pumpkin plant yield.

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

Growers should consider their markets and management practices to select a plant density that is appropriate for their goals. We recommend 10,764 plants/ha for high-volume production and 3588 plants/ha 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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