OPTIMIZING PLANTING ARRANGEMENTS FOR SWEET CORN AND SHORT-DAY ONION PRODUCTION IN GEORGIA

by

HAYLEY P. MILNER

(Under the Direction of Theodore McAvoy)

ABSTRACT

Georgia is ranked highly nationwide for vegetable production and it is a significant contributor to the state's economy, generating $1.3 billion in 2023. Sweet corn and short-day onion account for over one-quarter of the value brought by vegetables. While their value has kept pace with national prices, vegetable acreage has decreased in Georgia since 2019. To align with national values, there is a need to increase production efficiency on less acreage. Narrow row planting arrangements are commonly used in agronomic crops to improve production and enhance disease management. We investigated the effects of narrow row planting arrangements with variable in-row space on sweet corn and onion production. We found that narrow skip rows increased marketable yield in sweet corn without compromising ear quality, and that a narrow twin row, high density planting arrangement produced a favorable bulb size distribution with a higher percentage of high-value bulbs in short-day onions.

INDEX WORDS: *Zea mays* var. *rugosa*, *Allium cepa*, variable row spacing, planting arrangement, plant spacing, planting density, double row planting, twin row, Vidalia, vegetable production

OPTIMIZING PLANTING ARRANGEMENTS FOR CONVENTIONAL SWEET CORN AND SHORT-DAY ONION PRODUCTION

by

HAYLEY P. MILNER

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HAYLEY P. MILNER

Major Professor: Theodore McAvoy
Committee: Juan Carlos Diaz-Perez
Simerjeet Virk

Electronic Version Approved:

Ron Walcott
Vice Provost for Graduate Education and Dean of the Graduate School
The University of Georgia
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DEDICATION

To my parents, who taught me to love life and see the wonder in each day.

This one's for you dad, I'll see you on the other side.

ACKNOWLEDGEMENTS

After three years full of wonderful learning and hard work, I want to give thanks and gratitude to everyone that helped along the way. This was a group effort of considerable proportions by many people, and I'm lucky to have met and known y'all. Thank you.

First, a thank you to my advisor Dr. Ted McAvoy for introducing a lab rat (me) to the nuts and bolts of field production, and for his patience and guidance throughout my time here.

I want to thank my committee members, Dr. Juan Carlos Diaz-Perez and Dr. Simerjeet Virk, for lending their wisdom and expertise in academic research.

Special thanks to the McAvoy and Deltsidis team members for helping through all the blood, sweat, and tears that come along with getting a field from seed to harvest, as well as my fellow McAvoy students Nirmala Acharya, Elvis Pulici, and Emilio Suarez. You guys always lifted my spirits and offered your help whenever you could.

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CHAPTER 1

INTRODUCTION AND BACKGROUND

Vegetable crops are a significant contributor to the US economy, and sweet corn and onion are among the most popular vegetable crops (FAO 2018). Because demand for vegetables is expected to rise coupled with shrinking acreage, optimizing the efficiency of the land used for agricultural production is imperative for maximizing profitability (van der Mensbrugghe 2015; FAO 2018). Planting density and arrangement are key factors for plant development and yield, and there is a lack of recent studies focusing on plant population density in the major vegetable crops in the southeastern United States, of which Georgia is a major producer. A crucial distinction is that Georgia produces fresh market vegetables which means that in addition to yield, visual quality and appeal is also an imperative. In other crops such as processing sweet corn, breeding efforts in vegetables have produced hybrids that are much more tolerant to crowding stress (Tollenaar and Wu 1999; Dhaliwal et al. 2021). Given this, we expect that other vegetable crops may also possess this trait, so there is a need to re-evaluate current state guidelines to account for these factors while evaluating the impacts of adjusting plant populations. This study will address these needs with the following objectives:

1) Investigate photosynthetically active radiation (PAR) and plant growth under variable inter- and intra-row spacings and resultant planting densities for sweet corn

2) Evaluate the impact of planting arrangement and density on marketable yield for sweet corn and short-day (Vidalia) onion when irrigation and fertilizer inputs are held constant
3) Determine optimal planting arrangements to maximize efficiency for these vegetable crops

We expect to see that as plant populations increase, the canopy coverage for sweet corn will increase due to higher numbers of plants, resulting in increased light absorption per plot. Plants will likely grow taller at higher population densities than at lower population densities as a shade response. The overall yield per area is likely to increase, while the yield and fruit size for individual plants may decrease as plant populations are raised.

LITERATURE REVIEW

Economic importance

The state of Georgia ranks highly nationwide in vegetable production, with a value of $1.3 billion in 2023 (University of Georgia, Center for Agribusiness and Economic Development 2024). Sweet corn and short-day onion are two of Georgia's leading vegetable commodities, accounting for more than one-quarter of the value brought in by vegetables. With a world population expected to grow by 2.3 billion by 2050 increases in demand are predicted for the agricultural sector (van der Mensbrugghe 2015; FAO 2018). Although production is expected to rise globally, productivity is anticipated to level off over the coming decades (OECD/FAO 2023). This situation presents a challenge and an opportunity for regions such as Georgia in the southeastern United States, where continued innovation and efficiency could play a pivotal role in addressing forecasted productivity plateaus. For the US, in particular, production is driven primarily by consumer preferences such as visual appearance, aroma, and taste; the fresh market quality of vegetables is paramount to achieving profitability (Moser et al. 2011). Critical aspects of market quality and overall crop production include planting arrangement and planting density, which profoundly affect factors like vegetative growth, yield, and fruit characteristics (Botwright et al. 1998; Hashemi et al. 2005; Mohammad Hossein Aminifard 2012). Proper planting arrangements are critical for achieving optimal yields, which could be a key component of enhancing marketable yield for vegetable production in Georgia and the southeastern US. This approach can also help growers maximize productivity on increasingly declining acreage, and align with national and global demands for increased agricultural efficiency and productivity.

Influence of planting density on vegetative growth

When altering planting arrangements, a crucial consideration is the effect on planting density. Planting density strongly influences vegetative growth for factors such as leaf area, plant height, and dry mass in vegetable crops (Postma et al. 2021). Competition between plants for limited resources, such as nutrients, water, and light is a natural consequence when demands exceed supply, and is characterized by numerous physiological responses for enhancing performance in competitive environments. For example, the total dry mass follows a declining trend; conversely, leaf area tends to increase and plants tend to grow taller as an adaptation to reductions in light availability that occur with rising plant population densities (Craine and Dybzinski 2013; Postma et al. 2021). Such characteristics have been consistently observed in vegetable crops including field corn, bell pepper, okra, and tomatoes (Papadopoulos and Ormrod 1991; Mohammad Hossein Aminifard 2012; Maurya 2013; Djaman et al. 2022). These changes in growth habits can enable plants in competition to avoid shading and directly play into the capacity for light interception and photosynthetic capacity (Niinemets 2023). Importantly, when light reaching leaves is altered or restricted, such as through crowding and shading from neighbors, plants can react flexibly to optimize their photosynthetic capabilities. One notable change is stem elongation, which allows plants to potentially grow taller than competitors (Ballaré et al. 1990; Huber et al. 2021). Other changes can be observed as apical dominance, characterized by reduced branching or tillering (in grasses) in shaded conditions (Caton et al. 2003; Green-Tracewicz et al. 2011).

Crop yield and yield quality in response to planting density and arrangement

Many advancements in efficiency seen in agronomic crops can be attributed to improvements in hybrid performance of desired traits. In field corn, hybrid yield improvement has resulted in a greater tolerance to stressors such as planting density, among others (Tollenaar and Wu 1999; Duvick 2005). Altering plant populations (the number of plants in a space) and planting arrangements (how plants are arranged with each other in a space) directly impacts yield. Firstly, increasing the number of plants in a given area can help increase yield up to the point of excessive competition. In general, when plants experience excessive crowding stress and resource competition, they exhibit lower yields as a response to inadequate resources such as light, water, or soil nutrients (Papadopoulos and Ormrod 1991; Tollenaar et al. 1992; Jolliffe and Gaye 1995; Aroca 2012; Freschet et al. 2015). For sweet corn, this can mean a reduction in ears per plant, reduced ear size and a lower kernel count per ear (Tollenaar et al. 1992; Dhaliwal and Williams 2019). In root crops such as onion, space for development is a particularly important limiting factor on the yield; for instance, increasing planting density can increase yield in onions but also decreases bulb size (Brewster 2008). Adjusting planting arrangements is a method commonly used in agronomic crops to increase planting density by placing rows more closely together rather than decreasing plant space within the row. Planting arrangements are usually referred to by many names: narrow row, twin row, and skip row generally mean a plot that alternates row spacing between wide and narrow distances. In field corn, twin row cropping systems have been shown to improve drought tolerance while maintaining yield potential (Novacek et al. 2013), in soybeans, it can increase yield over single-row beds (Bruns 2011), and in peanuts, it increases yield as well as enhances disease management (Balkcom et al. 2010). Skip row planting is another method of maximizing yield while minimizing inputs where crops are planted in alternating wide and narrow rows as opposed to equidistant single rows. For example, a three-skip-one planting system consists of three rows at one distance, with an empty (non-crop) "skip" row between each group of three. In soybean and cotton, twin row planting coupled with skip row irrigation improved profitability in the Mississippi Delta region (Quintana-Ashwell et al. 2022). Because of the relative lack of research on alternative planting arrangements in vegetable crops, there is a need to investigate their potential and determine if they can improve productivity under planting arrangements adapted from agronomic production methods.

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CHAPTER 2

NARROW SKIP ROW PLANTING ARRANGEMENT PRODUCES HIGHER YIELD WITHOUT COMPROMISING EAR QUALITY IN FRESH MARKET SWEET CORN[1]

[1] Milner H, Diaz-Perez JC, Virk S, Luo X, Acharya N, & McAvoy T. (2025). To be submitted to *HortTechnology*.

ABSTRACT

Sweet corn (*Zea mays* var. *rugosa*) is among the most popular vegetables in the United States. In Georgia, most sweet corn is produced and shipped wholesale for fresh-market consumption, and is a significant contributor to the state economy. Planting arrangement and plant population density is a critical factor for achieving optimal yield while balancing resource inputs, and the commercial standard for sweet corn in the state is two equidistant rows spaced 36 in apart per plot at rates of 20,000 to 30,000 plants per acre. While recent research in the midwestern U.S. suggests that planting densities for processing sweet corn can be pushed above previously recommended ranges to optimize profit, little work has been done in recent years concerning fresh market shipper sweet corn in the southeastern region of the country. Therefore, the objective of this study is to optimize marketable yields by manipulating inter- and intra-row plant spacing. To do this, sweet corn (cv. 'Obsession') was sown directly to the field in the spring season of 2023 and 2024 in conventional (2) or narrow skip (3-skip-1) row planting arrangements 36 inches or 18 inches apart per bed top, resp., and five within-row spacings ranging from 6 inches to 10 inches at 1 inch increments. We found that total marketable yield was 20.2% higher on average for narrow row than conventional planting arrangements at 504.6 vs. 419.7 (± 10.4 standard error [SE]) bushel box/acre, and the estimated mean length of dehusked ears was 7.14 (± 0.03 SE) inches with no differences for row arrangement or in-row space. Plant height was also affected, and tended to be greater in narrow rows with height decreasing as in-row space increased, but did not change substantially in conventional arrangements. We found that while plants exhibited signs of crowding stress through changes in growth, a narrow skip planting arrangement can increase yield without compromising ear quality of fresh market sweet corn.

INTRODUCTION

Sweet corn (*Zea mays* var. *rugosa*) is among the most popular vegetables in the United States, with 343,000 acres in cultivation valued at $885 million in 2024 (US Department of Agriculture, National Agricultural Statistics Service 2024). In Georgia, most sweet corn is produced and shipped wholesale for fresh-market consumption, and contributes significantly to the state economy (University of Georgia 2023; University of Georgia, Center for Agribusiness and Economic Development 2024). Despite its value, statewide acreage and production have begun to decline compared with national averages. To keep up with national values, there is a need in Georgia to produce more efficiently to increase production value on less acreage. Optimizing planting density and row arrangement is well-studied in field corn to improve crop yield. In field corn, twin row (also known as narrow row) cropping systems have been shown to improve drought tolerance while maintaining yield potential (Novacek et al. 2013). Similar results have been reported in other agronomic crops: it can increase yield over single-row beds in soybeans (Bruns 2011), and it increased yield and enhanced disease management in peanuts (Balkcom et al. 2010). In soybean and cotton narrow row planting coupled with skip row irrigation improved profitability in the Mississippi Delta region of the US (Quintana-Ashwell et al. 2022). However, while planting densities for processing sweet corn in the midwestern US can be pushed above previously recommended ranges to optimize profit, little work has been done in recent years concerning fresh market shipper sweet corn in the southeastern region of the country, which differs drastically in soil type and seasonal weather patterns. Therefore, the objective of this study was to investigate a narrow skip (3-skip-1) row planting arrangement with different in-row spacings versus conventional planting arrangements on fresh market sweet corn yield and quality in Georgia.

MATERIALS AND METHODS

Site Selection and Study Design

The study was conducted at University of Georgia's Horticulture Hill Research Farm in Tifton, GA (*31°28'19.8"N, 83°31'48.3"W*) during the spring growing seasons of 2023 and 2024. This region is characterized by loamy sand soils and a subtropical climate with an average annual rainfall of 48 inches (NOAA – NCEI, 2024). Treatments were arranged in a randomized complete block design (RCBD) with four replicates. Each treatment was a combination of planting arrangement and within-row space between plants: conventional (two row, Figure 1.1A) or narrow skip (three row, Figure 1.1B) bed top arrangements spaced 36 inches or 18 inches between rows, respectively, and five within-row spacings of 6, 7, 8, 9, or 10 inches. This resulted in final planting densities of 29,000, 24,700, 21,800, 19,600, and 17,400 plants per acre for conventional two-row arrangements and 43,600, 37,000, 32,700, 29,400, and 26,100 plants per acre for narrow three-row arrangements, respectively (Table 2.1, Figure 2.1).

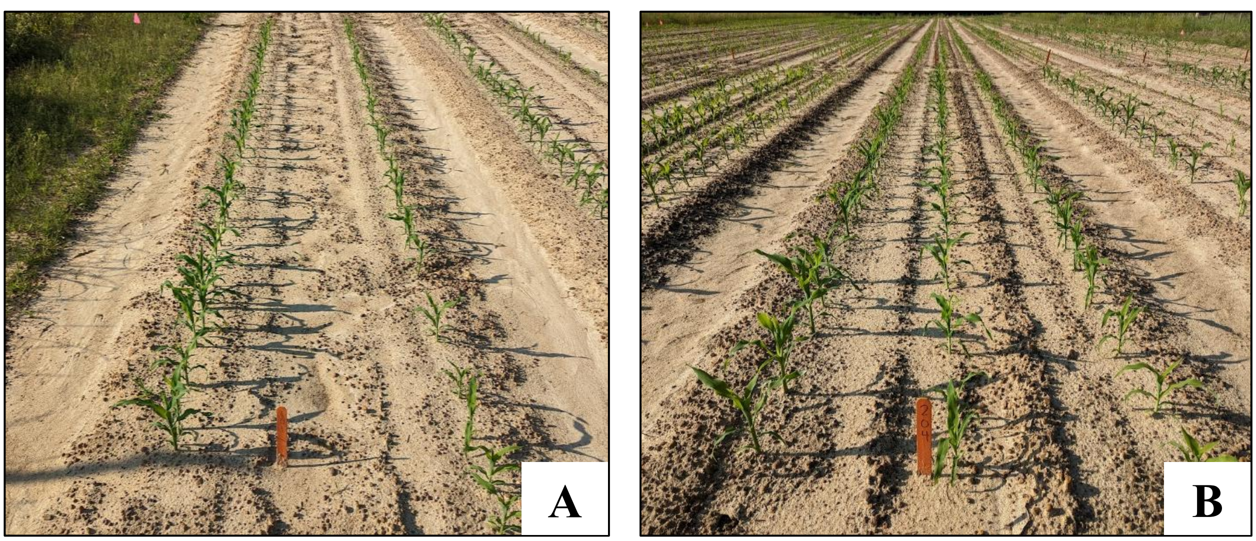

Figure 2.1. Images of conventional and narrow skip planting arrangements of sweet corn for trials in 2023 and 2024. (A) Conventional planting arrangement with 36 inches between rows. (B) Narrow skip (3-skip-1) planting arrangement with 18 inches between rows.

Table 2.1. List of treatments by planting arrangement, within-row spacing, and corresponding planting density of sweet corn for trials in 2023 and 2024.

	Planting density (plants/acre[i])	
Planting arrangement:	Conventional row (36 in[ii])	Narrow skip row (18 in)
In-row spacing (in)		
6	29,000	43,600
7	24,700	37,000
8	21,800	32,700
9	19,600	29,400
10	17,400	26,100

[i] 1 acre: 0.4047 ha
[ii] 1 in: 2.54 cm.

Experimental plots were 20 ft long and 6 ft center-to-center. The variety was Seminis' 'Obsession', a super sweet (*sh2*) bicolor hybrid chosen for excellent performance and common usage by growers in Georgia. Kernels were direct-seeded using a two-row Monosem NG+ vacuum planter (Monosem Inc., Kansas City, KS, USA). For pre-plant weed control, Dual II Magnum® (S-metachlor) and Atrazine (Syngenta, Greensboro, NC) was applied at a rate of 10 and 32 oz per acr, respectively. Post-emergence, Atrazine was applied at 32 oz per acre and Prowl® H2O (BASF, Florham Park, NJ) at 32 oz per acre. For fertilizer, prior to planting, 50 lbs N per acre of 10-10-10 N-P-K was applied followed by two side dress applications at 3 and 6 weeks after planting of 75 lbs N per acre of ammonium nitrate for a season total of 200 lbs N per acre.

Data collection

Plant height and photosynthetically active radiation (PAR) were measured 7 weeks after planting. Ten plants were selected at random within each plot, and height was measured from the base of the plant to the highest point in the arch of the newest fully unfurled leaf. PAR was measured between 11 am and 1 pm using the SF-80 Sunfleck PAR Ceptometer (METER Group, Inc., Pullman, WA, USA). A canopy-free initial PAR was measured for each plot before recording values from three roughly equidistant points within the plot. Each measurement, excluding the initial, was taken beneath the leaf canopy and across the plot diagonally and recorded in mol/m^2. Intercepted PAR was calculated as the difference between the initial measurement and canopy PAR, and then averaged across the three measurements of the respective plot. To avoid border effects, the inner 10 ft of each row in the plot was harvested for crop yield. Green ears ≥ 1.5 inches diameter were harvested at the milk stage (R3), then recorded by count per plot. A subsample of five randomly selected marketable ears from each plot was used to measure ear length, ear width, shank length and length of unfilled tips. Yield was converted and presented as bushel boxes per acre, where one bushel box holds 48 ears of corn graded to USDA Fancy standards for fresh market sweet corn (ear length > 6 inches) (United States Department of Agriculture, Agricultural Marketing Service 1992; University of Georgia 2023).

Statistical Analysis

Data were analyzed using R Statistical Software v.4.2.2 (R Core Team 2022). A linear model was used to estimate treatment effects and detect differences between the number of rows per plot and in-row space between plants. Row arrangement, space between plants within the row (in inches), year, and replication were considered fixed effects, and interactions between rows, space, and year were evaluated according to the following model: Response = Rows × Space × Year + Block. Model residuals were tested for normality and homoscedasticity using a significance level of $\alpha = 0.05$. The intercepted PAR was heteroscedastic with a strong right skew and non-parametric with respect to year; therefor linear regression was performed separately for each year.

Post-hoc separation of estimated marginal means (emmeans) was determined with Tukey's Honest Significant Difference. Figures were generated using RStudio v.2024.04.02 (RStudio Team 2024).

RESULTS

Yield, ear quality, and plant growth responses to planting arrangement

Plant height changed with planting arrangements, there was an interaction effect, and the impact of in-row space on height was more substantial in narrow rows than in conventional row arrangements. Plants tended to be taller in narrow rows with height decreasing as in-row space increased, but did not change substantially in conventional arrangements (Fig. 2.2).

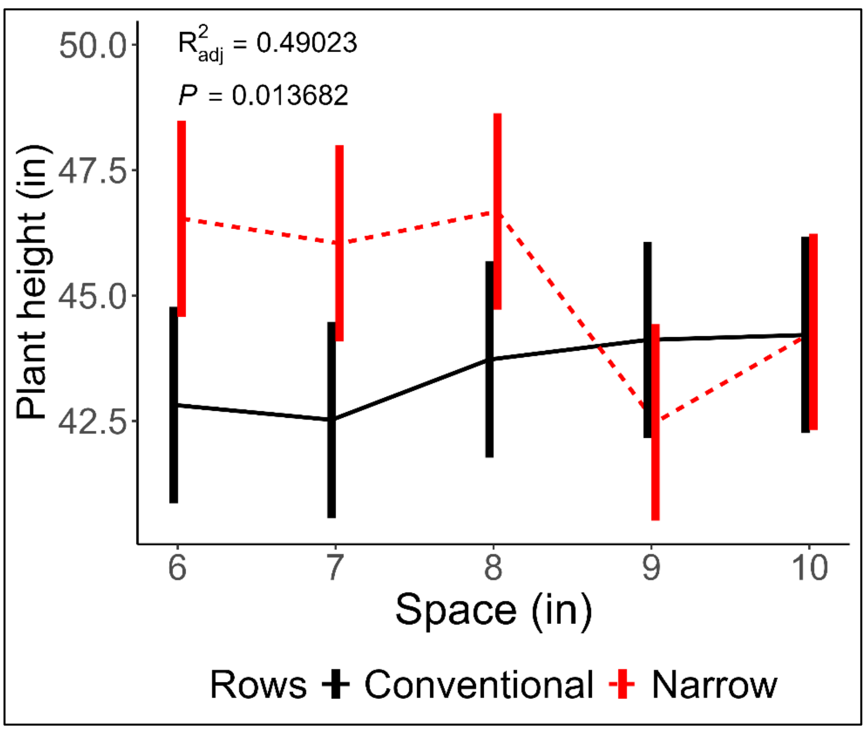

Figure 2.2. Interaction plot for estimated marginal means of plant height (inches) with in-row space (inches) as x-axis for sweet corn with years 2023 and 2024 combined. Bars represent 95% confidence intervals (CIs). Points with less than 50% overlap are significantly different.

The intercepted PAR was not affected by in-row space and was higher for plants in narrow rows in 2023, but this trend was not seen in 2024 (Fig. 2.3).

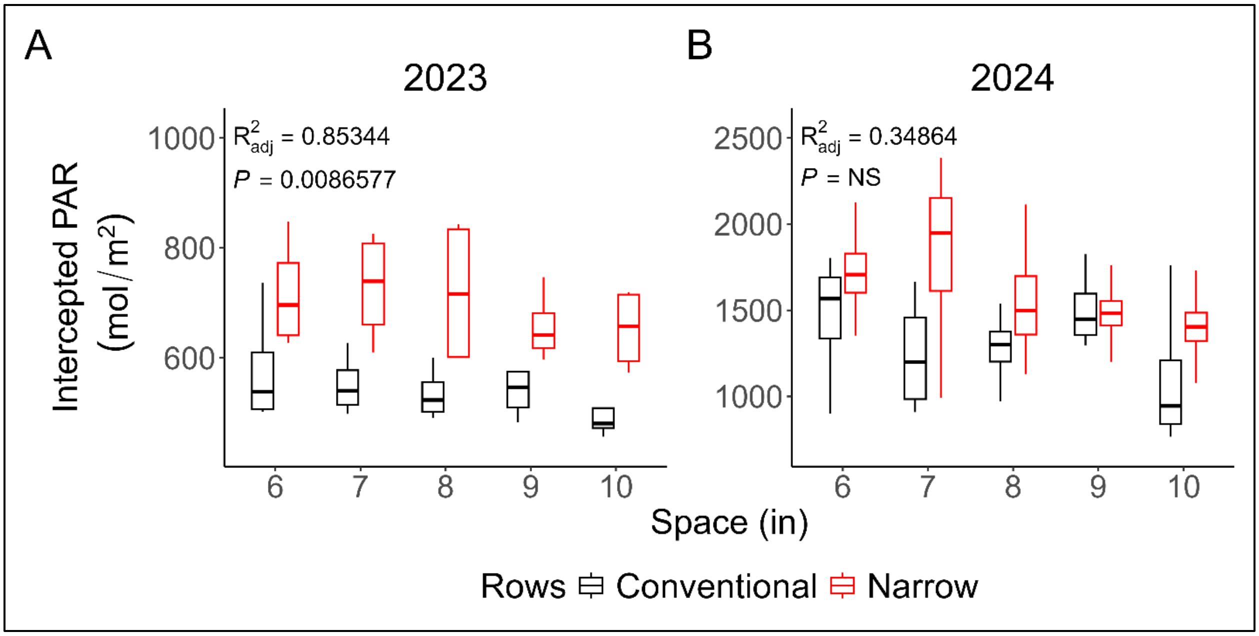

Figure 2.3. Box plot of intercepted PAR (mol/m^2) by in-row space (inches) for sweet corn in 2023 (A) and 2024 (B).

Total marketable yields were 20.2% higher on average for narrow row than conventional planting arrangements at 504.6 vs. 419.7 (10.4 standard error) bushel box/acre, respectively, with no significant differences between in-row spacing (Fig. 2.4).

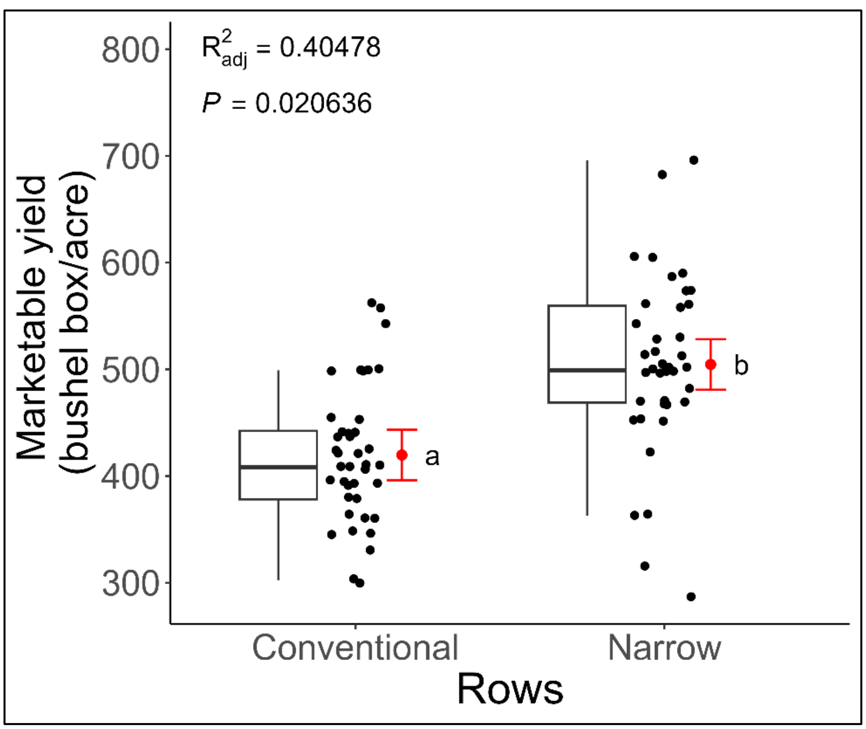

Figure 2.4. Box plot comparing marketable yield (bushel box/acre) of sweet corn for conventional and narrow skip planting arrangements with 2023 and 2024 combined. Black jittered points represent individual measurements. Red dots represent model estimated marginal means, and red bars indicate standard error.

Ear length was not strongly affected by planting arrangement, although some quality characteristics were influenced. The estimated mean length of dehusked ears was 7.14 ± 0.03 SE inches (Fig. 2.5) with no differences for row arrangement or in-row space.

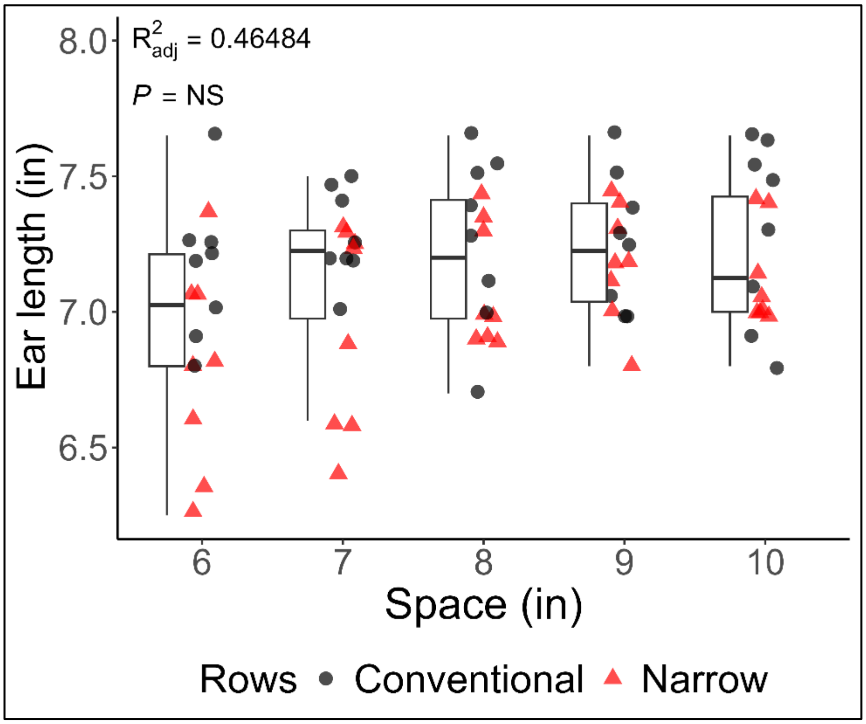

Figure 2.5. Box plot indicating ear length (inches) by in-row space (inches) of sweet corn with years 2023 and 2024 combined. Black jittered points represent measurements from conventional row arrangements, and red jittered triangles represent narrow skip row arrangements.

Ear width was also unaffected by row arrangement or in-row spacing; however, there was a significant difference between years (2.08 vs. 1.66 [0.01 SE] inches for 2023 and 2024, resp.) (Fig. 2.6).

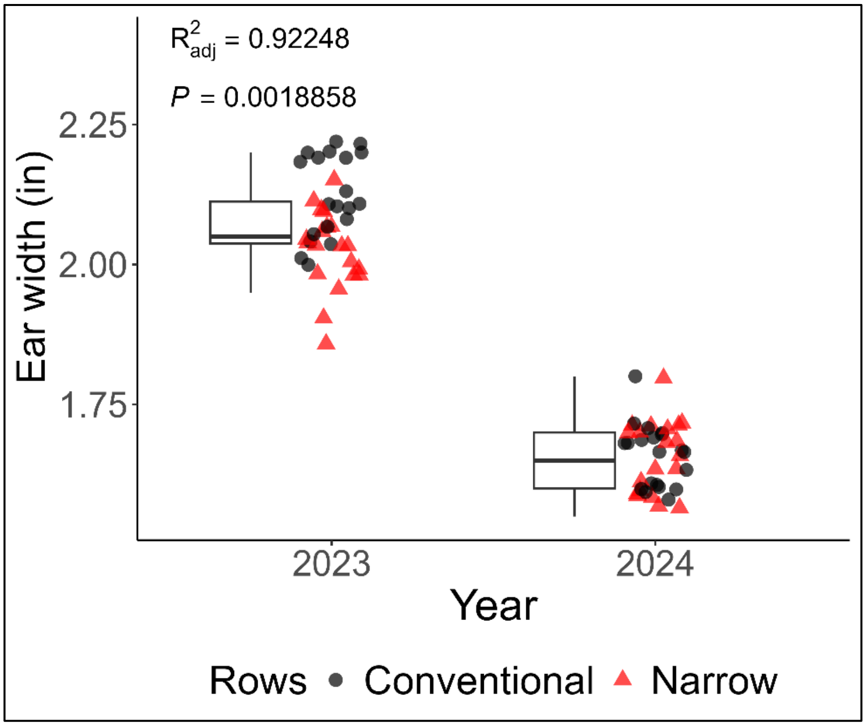

Figure 2.6. Box plot of ear width (inches) for sweet corn by year with row arrangements combined. Black jittered points represent measurements from conventional row arrangements, and red jittered triangles represent narrow skip row arrangements.

The mean length of the shank (the portion of the lateral branch below the ear) was estimated at 3.27 (0.06 SE) inches and increased with in-row spacing by ~0.20 inches per inch of increased space but was not different between row arrangements (Fig. 2.7).

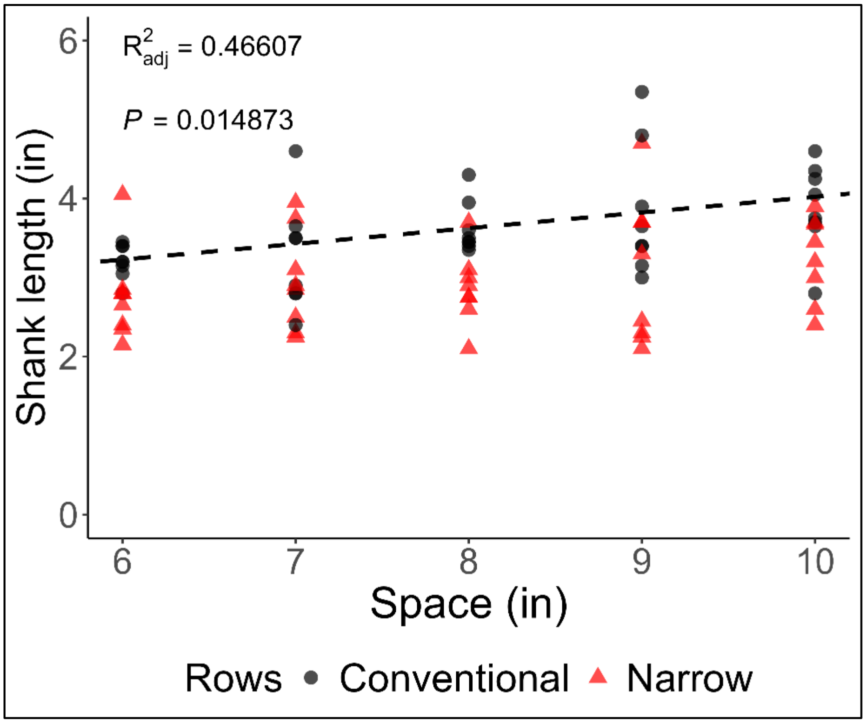

Figure 2.7. Model estimated regression of shank length (inches) by in-row space (inches) for sweet corn with years 2023 and 2024 combined. Black jittered points represent measurements from conventional row arrangements, and red jittered triangles represent narrow skip row arrangements.

Finally, there was an interaction effect between kernel tip fill, row arrangement and in-row spacing. The impact of in-row space was greater for conventional row arrangements; the area of unfilled tip kernels decreased as in-row space increased. However, in narrow rows there was little difference between in-row spacing (Fig. 2.8).

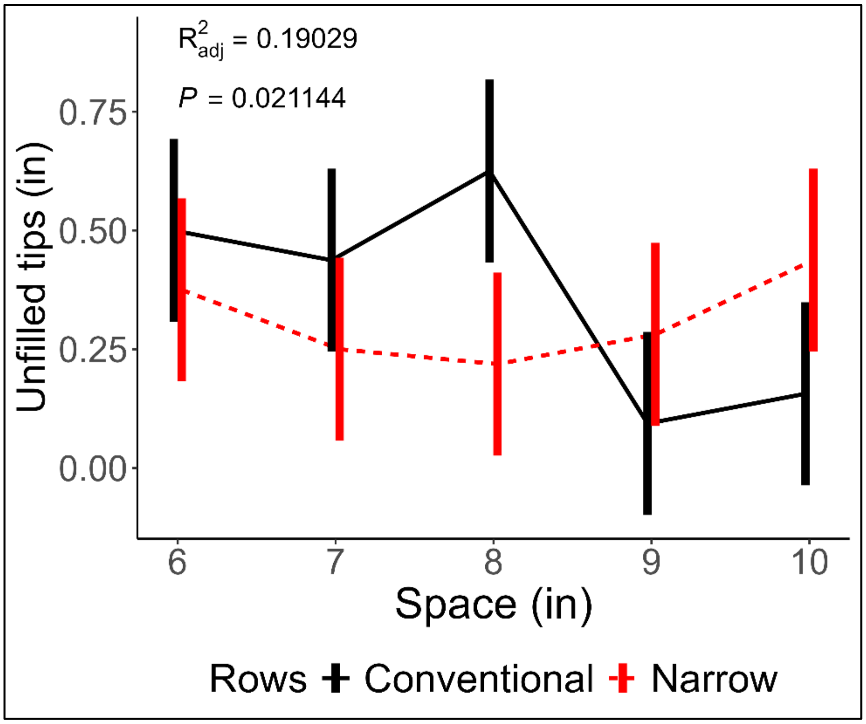

Figure 2.8. Interaction plot for estimated marginal means of unfilled tips (inches) of sweet corn with in-row space (inches) as x-axis with years 2023 and 2024 combined. Bars represent 95% confidence intervals (CIs). Points with less than 50% overlap are significantly different.

DISCUSSION

Plant growth responses to planting arrangement

Altering planting arrangements and plant population has a direct impact on growth and yield. We observed substantial differences in height between narrow skip and conventional row arrangements. Plants tended to be taller in narrow skip plots, and the effect of space was larger in narrow skip arrangement than for conventional planting arrangements. Planting density and arrangements strongly influence growth in vegetable crops; competition for limited resources is a natural consequence when demands exceed supply, characterized by numerous physiological responses to enhance performance in competitive environments. In response to crowding stress, plants tend to grow taller as an adaptation to reductions in light availability (Craine and Dybzinski 2013; Postma et al. 2021). This has been well documented in maize through changes in the leaf canopy and light interception (Williams 2016; Song et al. 2016; Sher et al. 2018). While we did record differences in measured light interception in 2023, these results weren't observed in 2024. In 2023, plants in narrow skip plots had higher estimated light interception- this intuitively makes sense because there are more plants in those plots on average, so the leaf area may also be higher than in conventionally arranged plots. However, we did not observe such differences in estimated light interception between narrow skip plots and conventional rows in 2024. There were no visible signs of nitrogen deficiency such as yellowing, but while not statistically significant, plants trended taller on average in 2024 and yields were slightly lower. One potential explanation is that plants in 2024 may have been under more stress: the 2024 trial experienced more rainfall in May followed by less rain in June, as well as higher temperatures in both months compared to the weather in 2023 (University of Georgia Weather Network 2024).

Yield and ear quality responses to planting arrangement

A consequence of excessive crowding stress and resource competition is lower yields in response to inadequate resources (Papadopoulos and Ormrod 1991; Tollenaar et al. 1992; Jolliffe and Gaye 1995; Aroca 2012; Freschet et al. 2015). For sweet corn, this can mean a reduction in ears per plant and reduced ear size (Tollenaar et al. 1992; Dhaliwal and Williams 2019). We saw higher yields on average in the narrow skip rows, although in-row space was not a significant predictor of yield. This can likely be attributed to the higher plant populations in general in narrow skip (33,760 plants/acre) compared to conventional row arrangements (22,520 plants/acre). Ear length and width were not significantly affected by in-row space or planting arrangements; while they tended to decrease as space decreased, they remained within preferences for fresh market quality for ears greater than 6 inches long and 1.5 inches wide (United States Department of Agriculture, Agricultural Marketing Service 1992; University of Georgia 2023). Our results are similar to Dhaliwal and Williams (2019), where the authors found that ear length and mass decreased linearly as planting density increased, and that increasing plant density could improve yield for processing sweet corn in the midwestern US. Our findings indicate that the plant populations resulting from the combinations of row arrangement and in-row space were high enough to increase yield, without causing excessive crowding stress and affecting ear quality, and that overall a narrow skip, 3-skip-1 planting arrangement, while susceptible to some crowding stress, is a suitable method to improve fresh market sweet corn production in Georgia.

CONCLUSIONS

To conclude, while we found that plants exhibited signs of crowding stress through changes in growth, a narrow skip planting arrangement can increase yield without compromising the ear quality of fresh market sweet corn. Producers can adapt this planting arrangement without requiring any changes in crop management, and it is a suitable strategy to improve efficiency in sweet corn production.

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CHAPTER 3

HIGH PLANTING DENSITY TWIN-ROW ARRANGEMENT PRODUCES FAVORABLE BULB SIZE DISTRIBUTION IN SHORT-DAY ONION[2]

[2] Milner H, Diaz-Perez JC, Virk S, Luo X, Tyson C, & McAvoy T. (2025). Accepted by *HortTechnology*.

ABSTRACT

Twin-row planting arrangements are commonly used in agronomic crops to improve production and enhance disease management, but little information exists on their application in onion production. This study evaluated the impact of twin-row arrangements at high planting density on yield and bulb size distribution of short-day onion (cv. ‘Sweet Magnolia’). Treatments combined within-row and between-row distances and the number of rows per bed top to achieve the desired planting arrangement and resultant planting densities. Treatments were four single rows of plants per bed top spaced 6 in × 12 in (within- by between-row), four single rows spaced 4 in × 12 in, or four twin rows (eight rows in total) spaced 6 in × 4 in among twins with 12 in between twin-row pairs from middle to middle, resulting in planting densities of 58,000, 87,000 (commercial standard), and 116,000 plants per acre, respectively. Onion total and marketable yields increased while bulb size decreased as planting density rose. The twin-row high planting density was equivalent to the commercial standard in both total and marketable yield. Most importantly, twin rows had a favorable bulb size distribution, with both the highest yield and percentage of jumbo bulbs (≥ 3 inches in diameter) at 998.3 40-lb bags per acre and 80.2%, respectively. Culls decreased with increased planting density with no difference between twin-row high planting density and the commercial standard. Significant bolting was observed in 2024 at high planting density in conjunction with cooler weather. Our data indicates that twin-row planting arrangements do not outperform the commercial standard planting density in marketable yield but have potential applications for targeting specific bulb sizes by altering the bulb size distribution to favor smaller bulbs.

INTRODUCTION

Onions (*Allium cepa*) are a highly valued vegetable crop in the United States; 133,000 acres are devoted to onion cultivation, worth just over $1.5 billion [US Department of Agriculture (USDA), National Agricultural Statistics Service, 2023]. In Georgia, onions are worth $178 million and contribute 13% of the total value brought by vegetables (University of Georgia, Center for Agribusiness and Economic Development, 2024). Georgia is known for the Vidalia onion, which is valued for its sweet taste and low pungency. This onion is a yellow granex type exclusively cultivated in the Vidalia region of Georgia- a federally designated area well-suited for sweet, short-day onions because of its environment: loamy sand soils with low sulfur content and mild winters (Boyhan and Torrance, 2002).

Each onion plant only produces one onion bulb. Thus, planting density is crucial to optimize yields and bulb size. Currently, most growers plant Vidalia onions in four single rows per bed top with 4 to 6 inches between plants to reach rates of 58,000 to 87,000 plants per acre (University of Georgia, 2017). Increasing planting density can increase yield in onions but also decrease bulb size (Brewster, 2008). This presents a challenge because bulb size distribution is an important factor of onion yield: consumers prefer jumbo bulbs (≥ 3 inches in diameter), which bring the highest premium at the market and are a priority for growers (Ibiapina de Jesus, 2023). Typically, growers change the spacing between plants within a row to reach their target planting density, but decreasing the space below 4 inches (10 cm) would likely restrict the growth of larger bulbs. This has been reported in short-day onions: Leskovar et al. (2012) noted significant decreases in jumbo bulbs when decreasing in-row space from 4 in to 3.2 in, and Stofella (1996) also reported a reduction of bulbs ≥ 3 in in diameter from 6 to 3 in in-row space.

Twin-row planting arrangements are a common technique for agronomic crops that can be used to increase planting density by placing rows more closely together instead of decreasing plant space within the row. In soybeans, it can increase yield over single-row beds (Bruns, 2011), and in peanuts, it increases yield as well as enhances disease management (Balkcom et al., 2010), but little information exists regarding its effect in onions. Because each onion plant produces a single bulb, using a twin-row planting arrangement that doesn't put plants closer than 4 in to increase planting density may improve yields without reducing desirable onion sizes. The goal of this research was to increase production efficiency, yields, and profitability using equipment growers already have. Applying this technique to onions can be implemented using existing equipment (tractor, sprayers and spreaders), only the hole punch needs to be modified, without altering standard management practices or reducing the in-row space below 4 in. This study evaluated the effects of a high plant density twin-row planting arrangement on yield and yield components of Vidalia onion.

MATERIALS AND METHODS

Site selection and study design

The study was conducted at the University of Georgia Vidalia Onion and Vegetable Research Center (VOVRC), located in Lyons, Georgia, during the winter growing seasons of 2023 and 2024 (*32°00'59" N, 82°13'12" W*). This region is ideal for Vidalia onion production due to the loamy sand soils with low sulfur content and warm, humid weather with an average annual rainfall of 46 inches (University of Georgia Weather Network, 2024; USDA, National Resources Conservation Service, 2013).

Trials were arranged in a randomized complete block design (RCBD) with three treatments and four replications. Treatments combined within-row, between-row spacing, and number of rows per bed to achieve the desired planting arrangements and resultant plant population densities. Hole punch wheels with three different spoke configurations (shown in Fig. 3.1) were mounted at four wheels per bed top and spaced 12 in from wheel middle-to-middle to form main rows.

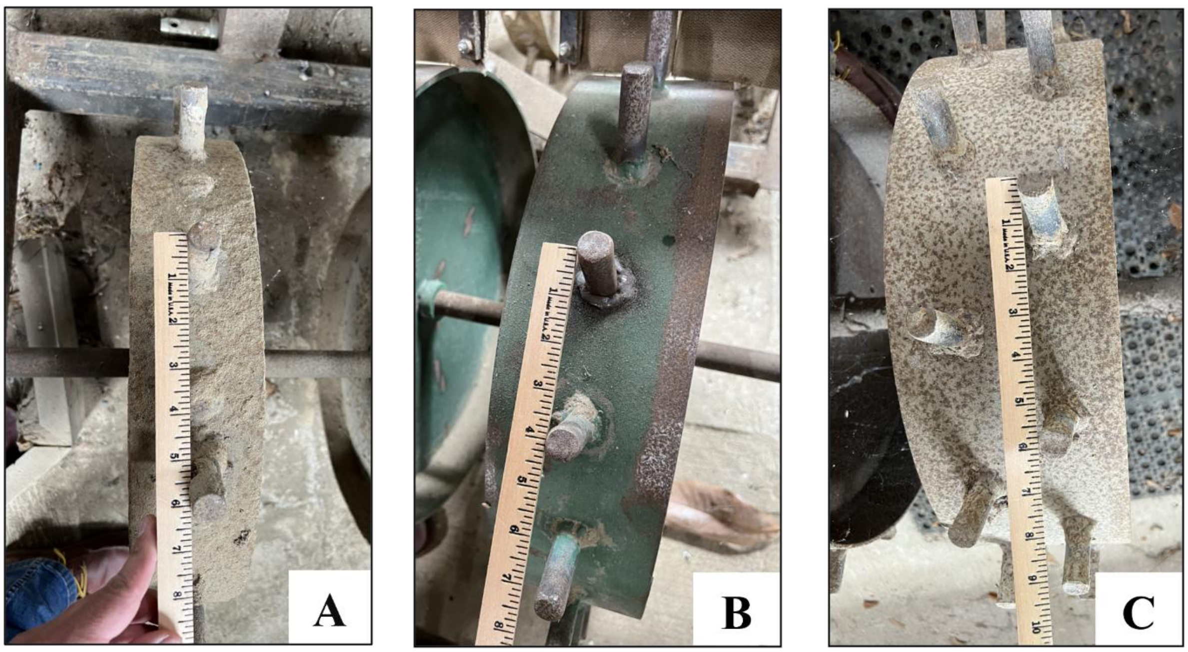


Figure 3.1. Images of hole-punching attachments used for single and twin-row onion planting arrangements pictured with a wooden yardstick in inches for scale. (A) Single row wheel attachment with 6 in between spokes. (B) Single row wheel attachment with 4 in between spokes. (C) Twin-row wheel attachment with 6 in between spokes and 4 in between twins. 1 in: 2.54 cm.

Configurations were four rows of plants spaced 6 in within-row (Fig. 3.1A), four rows of plants spaced 4 in within-row (Fig. 3.1B), or four staggered twin-rows (eight rows total) spaced 6 in within the row and 4 in between twin-rows on the same hole puncher (Fig. 3.1C), resulting in planting densities of 58,000, 87,000, and 116,000 plants per acre, respectively (Table 3.1). Treatment plots were 20 ft long and 6 ft center-to-center.

Table 3.1. List of treatments by planting arrangement, planting density, rows per bed top, and corresponding spacing of onions for trials in 2023 and 2024.

Planting arrangement	Planting density (plants/acre)[i]	Rows per bed	Spacing (inches)	
			In-row	Between-row[ii]
Single row	58,000	4	6	12
Single row	87,000	4	4	12
Twin row	116,000	8[iii]	6	12[iv]

[i] 1 acre: 0.4047 ha
[ii] Between-row distance is measured from middle to middle of the hole punch wheel attachment.
[iii] Four twin rows = eight rows total.
[iv] Distance between twins on the same wheel attachment is 4 inches with 12 inches between twin rows. See figure 1C.

The variety studied was "Sweet Magnolia" (Seminis, St Louis, Missouri, USA), chosen based on superior crop performance and common usage by growers in Georgia. Bare ground seedlings that were 60 days old were transplanted in the first week of December and harvested in the last week of April. Fertilizer, irrigation, and pesticide management were followed according to University of Georgia guidelines for onions. At harvest, onion bulbs were undercut with a rotating bar when 40%-50% of the tops had fallen over. These bulbs were allowed to field-dry for five days before trimming roots and tops. They were then stored in plastic mesh bags and cured in a dryer at 90 F for 48 hours (h).

Data collection

Each plot's total bulb weight was recorded post-cure on a per-plot basis. Bulbs that were diseased, misshapen, or hollow-necked were considered culls and removed before sizing. The remaining marketable onions were sized by USDA grading standards for Granex-type onions (USDA, Agricultural Marketing Service, 2014) using a commercial perforated conveyor belt grader (Haines Equipment Inc, Avoca, NY, USA) and bulb weights were recorded for each size by plot. Size categories were based on minimum bulb diameter with medium = 2 inches, jumbo = 3 inches, and colossal = 3.75 inches. In 2024, the number of bolting plants in each plot was recorded after observing substantial bolting in the field, which was absent in 2023.

Statistical analysis

Yield and yield parameters were analyzed using a Mixed Model in JMP Pro version 17 (SAS Institute Inc., Cary, NC, 2024) to determine significant differences between single-row low and standard planting density and twin-row high planting density treatments at $\alpha = 0.05$, with treatment as a fixed effect and year and block as random effects. Bolting in 2024 was analyzed similarly, excluding year from the model. Post-hoc separation of means was determined using Tukey's Honest Significant Difference. Supplemental figures were generated in RStudio version 2024.04.02 (RStudio, PBC., Boston, MA, 2020).

RESULTS

Yield response to planting density

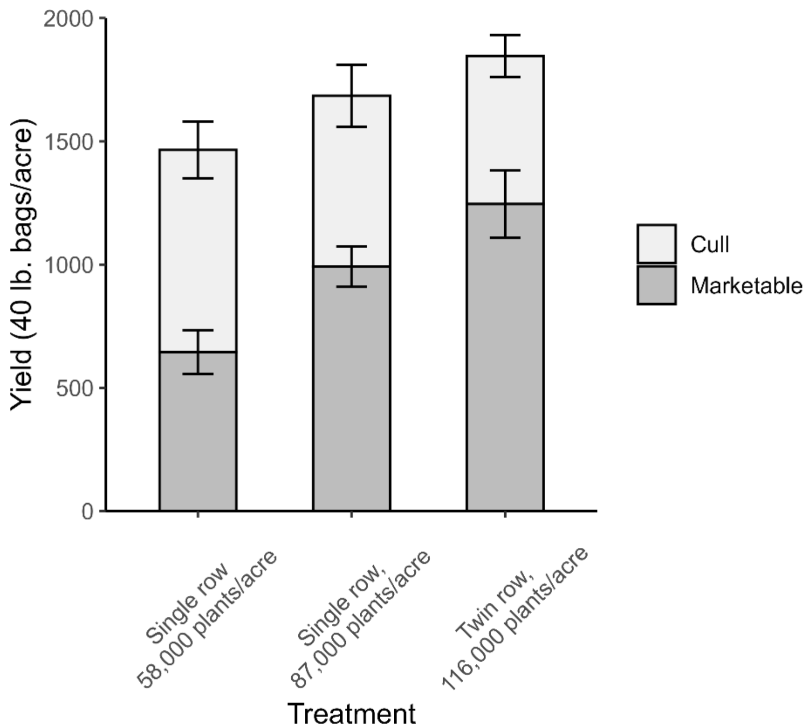
Both total and marketable yields increased with planting density (Table 3.2; Supplemental fig. 3.1).

Table 3.2. Total, marketable, and cull yield of onion by weight and percentage of marketable and cull bulbs relative to total yield at each planting arrangement and density in 2023 and 2024 combined. Values represent descriptive means ± standard error.

Planting arrangement	Planting density (plants/acre)	Yield (40 lb. bag/acre)[1]				
		Total	Marketable	Cull	% Marketable	% Cull
Single row	58,000	1465.0 ±136.32 b[ii]	644.9 ± 88.9 b	820.2 ± 114.8 a	45.0 ± 4.7 b	55.0 ± 4.7 a
Single row	87,000	1684.5 ± 194.1 ab	991.4 ± 81.9 ab	693.1 ± 125.8 ab	60.9 ± 3.0 a	39.1 ± 3.0 b
Twin row	116,000	1846.2 ± 173.9 a	1245.5 ± 137.0 a	600.7 ± 85.6 b	66.7 ± 4.5 a	33.3 ± 4.5 b

[i] 40 lb. bag/acre: 98.84 lb/ha or 18.14 kg/ha

[ii] Letters following means represent separation by Tukey's HSD test within the column, with unique letters indicating a significant difference at $P \leq 0.05$.



Supplementary figure 3.1. Total yields for onion displaying the mean contribution of marketable and cull bulbs for different planting arrangements (single row 58,000 plants/acre, single row 87,000 plants/acre, or twin row 116,000 plants/acre), with years 2023 and 2024 combined. Error bars represent standard error of the mean and are located at the top of the bar for the respective bulb category. 40 lb. bag/acre: 98.84 lb/ha or 18.14 kg/ha.

The twin row high planting density had a significantly higher total yield than the lowest planting density (P = 0.0146). Planting using a twin-row configuration at 116,000 plants/acre yielded significantly higher 40 lb. bag/acre (1846) than planting in single rows at 58,000 plants/acre (1465). The total yield for the commercial standard density of single rows at 87,000 plants/acre (1684) was not significantly different from the other two treatments ($\alpha = 0.05$).

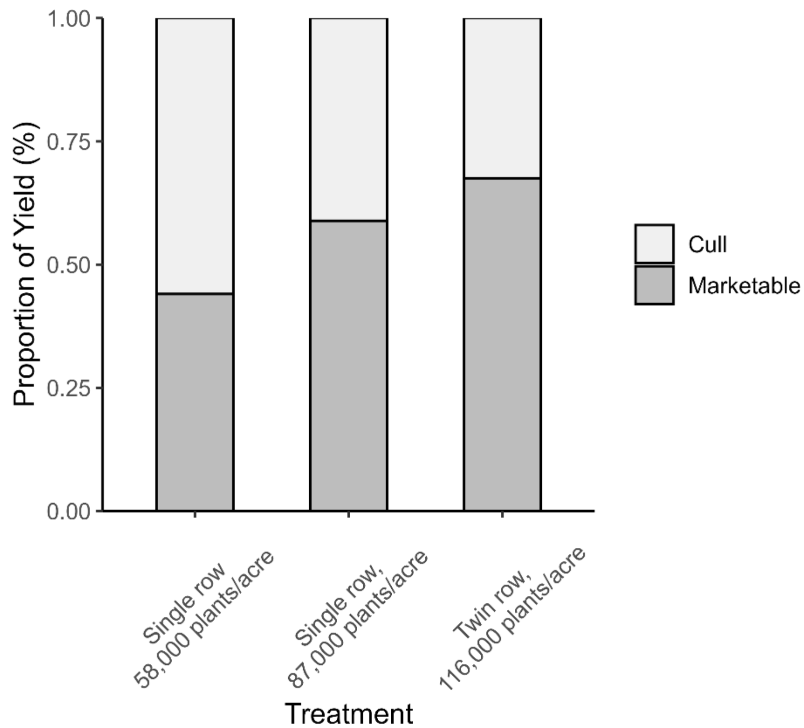
Marketable yield followed a similar pattern, with a significantly higher yield from the twin-row 116,000 plants/acre plots than the 58,000 plants/acre plots in single rows (P = 0.0017). No significant differences existed in marketable yield between the commercial standard and the high and low planting density treatments ($\alpha = 0.05$) (Table 3.2).

In 2024, plots with the highest planting density experienced significantly more bolting (seed-stem formation) at 15.9% (Table 3.3). The proportion of marketable to cull bulbs increased substantially with planting density, with the percentage of marketable bulbs rising from 45% at the low density to 60.9% and 66.7% ($P = 0.0034$) for the 87,000 plants/acre commercial standard and high planting density, respectively (Table 3.2; Supplemental fig. 3.2). There was no significant difference in culls between the single-row commercial standard and the twin-row high planting density.

Table 3.3. Percentage of bolted onion plants by planting arrangement and density in 2024. Values represent descriptive means ± standard error.

Planting arrangement	Planting density (plants/acre)[i]	Bolted plants (%)
Single row	58,000	0.5 ± 0.3 b[ii]
Single row	87,000	2.1 ± 0.6 b
Twin row	116,000	15.9 ± 1.3 a

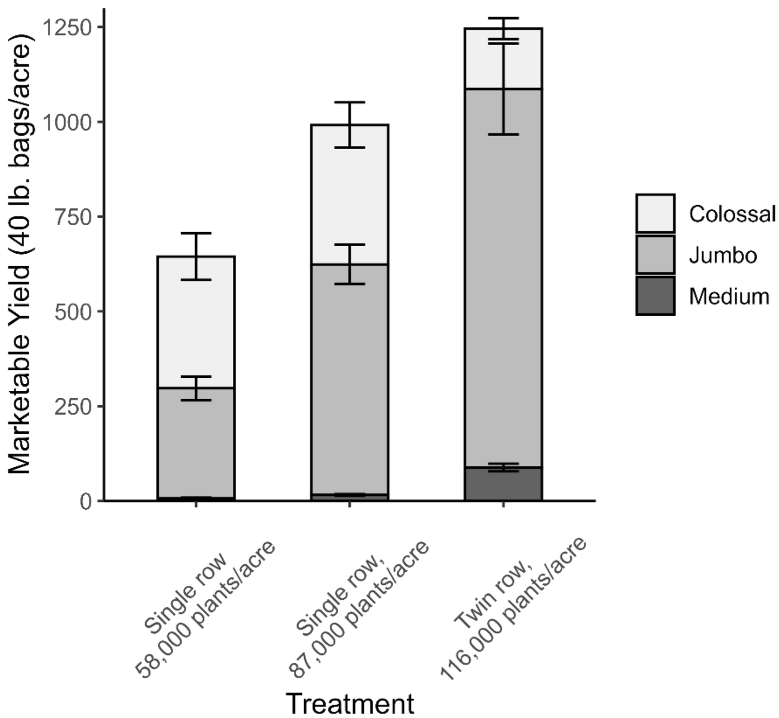
[i] 1 acre: 0.4047 ha
[ii] Letters following means represent separation by Tukey's HSD test within the column, with unique letters indicating a significant difference at $P \leq 0.05$.



Supplementary figure 3.2. Mean proportion of marketable and cull bulbs to the total yield of onions grown under different planting arrangements (single row 58,000 plants/acre, single row 87,000 plants/acre, or twin row 116,000 plants/acre), with years 2023 and 2024 combined. 1 acre: 0.4047 ha

Bulb size distribution in response to planting density

The relative contribution of each bulb size category to the marketable yield was also affected by planting density. The proportion of jumbo- and medium-sized bulbs was the largest, and the fraction of colossal bulbs was the smallest, with twin-row 116,000 plants/acre plots (Table 3.4; Supplemental figs. 3.3 and 3.4).



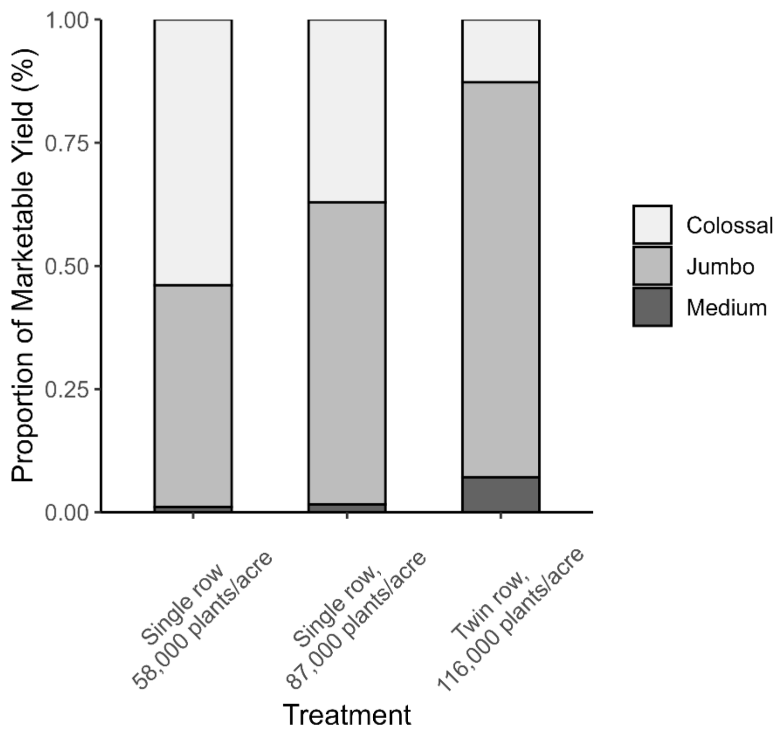
Supplementary figure 3.3. Marketable yield for onion displaying the mean contribution of Colossal, Jumbo, and Medium bulb sizes for different planting arrangements (single row 58,000 plants/acre, single row 87,000 plants/acre, or twin row 116,000 plants/acre), with years 2023 and 2024 combined. Error bars represent standard error of the mean and are located at the top of the bar for the respective size category. Size categories were based on the minimum diameter of bulbs: Colossal = 3.75 inches, Jumbo = 3 inches and Medium = 2 inches. 1 in: 2.54 cm. 40 lb. bag/acre: 98.84 lb/ha or 18.14 kg/ha.

Table 3.4. Contribution of onion bulb size by weight to the marketable yield by planting arrangement and density in 2023 and 2024 combined. Values represent descriptive means ± standard error.

Planting arrangement	Planting density (plants/acre)[ii]	Yield (40 lb. bag/acre)[i]		
		Colossal[iii]	Jumbo	Medium
Single row	58,000	347.7 ± 61.9 ab[iv]	290.4 ± 30.7 c	6.8 ± 2.3 b
Single row	87,000	367.5 ± 59.7 a	608.0 ± 52.0 b	15.9 ± 2.3 b
Twin row	116,000	158.8 ± 28.0 b	998.3 ± 119.8 a	88.5 ± 10.1 a

[i] 40 lb. bag/acre: 98.84 lb/ha or 18.14 kg/ha
[ii] 1 acre: 0.4047 ha
[iii] Size categories were based on the minimum diameter of bulbs: Colossal = 3.75 inches, Jumbo = 3 inches and Medium = 2 inches. 1 in: 2.54 cm

[iv] Letters following means represent separation by Tukey's HSD test within the column, with unique letters indicating a significant difference at $P \leq 0.05$.



Supplementary figure 3.4. Mean proportional bulb size distribution of Colossal, Jumbo, and Medium onion bulbs to the marketable yield for different planting arrangements (single row 58,000 plants/acre, single row 87,000 plants/acre, or twin row 116,000 plants/acre), with years 2023 and 2024 combined. Size categories were based on the minimum diameter of bulbs: Colossal = 3.75 inches, Jumbo = 3 inches and Medium = 2 inches. 1 in: 2.54 cm. 1 acre: 0.4047 ha.

Jumbo bulbs were a significant contributor to marketable yield (40 lb. bags/acre) for 58,000 plants/acre plots at 290.4 (45.0%), and the largest contributor for both commercial standard 87,000 plants/acre and twin-row 116,000 plants/acre plots at 608.0 (61.3%) and 998.3 (80.1%), respectively, with statistical differences between each group ($P < 0.0001$). Medium bulb yields (40 lb. bag/acre) were highest in twin-row 116,000 plants/acre plots at 88.5 (7.1%) and statistically distinct from the group of single-row low and commercial standard density plots with yields of 6.8 (1.0%) and 15.9 (1.6%), respectively ($P < 0.0001$).

Yields (40 lb. bag/acre) for colossal bulbs were highest in the single-row 58,000 and 87,000 plants/acre plots at 347.7 (53.9%) and 367.5 (37.1%). The twin-row high planting density had lower yields of colossal bulbs at 158.8 (12.7%) than the commercial standard but was not significantly different from the single-row low planting density plots ($P = 0.032$). The single-row low and commercial standard plant density plots were not significantly different.

DISCUSSION

Yield and planting density

Twin-row planting arrangements are a common technique for agronomic crops that can increase yield and enhance disease management. Our goal was to apply twin-row planting to Vidalia onions as a form of precision agriculture and evaluate the impact at a high planting density. We observed total and marketable yields increase with planting density. However, while the twin-row high planting density had higher total and marketable yields than the low planting density, it was equivalent to the commercial standard for both yield categories. Since each plant produces one bulb, these yield increases were primarily due to increasing plant numbers. Mixed results were found in Spanish sweet onions. Stofella (1996) saw yields increase with planting density at rates ranging from 101,000 to 608,000 plants per acre, while Caruso et al., (2014) reported no effect of planting density on yield for rates of 524,000, 672,000, and 941,000 plants per acre. In contrast with these studies is a report from Brazil where short-day onions showed a quadratic yield response to plant spacing (dos Santos et al., 2018). In our study, cull bulbs also decreased with planting density, and there was no difference between the twin-row high planting density and the commercial standard. This contrasts with Stofella (1996), where culls were < 9% and not affected by planting density. Because we applied the same rate of fertilizer across planting densities, one possible explanation for the higher number of culls at low planting densities is excess available nitrogen (N), which has been associated with bulb decay in Vidalia onions (Diaz et al., 2003).

Bulb size distribution and planting density

Bulb sizes generally decreased as planting density increased, with significant differences in size distribution. Jumbo and medium bulbs increased with planting density, and the twin-row high planting density plots had both the highest yield and percentage of these bulbs. Results for colossal bulbs were mixed. Colossal bulbs tended to decrease as planting density increased, but the differences between the lowest planting density and the other treatments were not significant. This is generally consistent with previous reports on short-day onions: Stofella (1996), Leskovar et al. (2012), Caruso et al. (2014), and dos Santos et al. (2018) all observed decreasing bulb sizes as planting density increased. Varietal and environmental factors also influence the effect of planting density on yield and bulb sizes.

Boyhan et al. (2009) observed decreased bulb sizes for Vidalia onions at rates from 31,680 to 110,880 plants per acre but noted significant varietal and environmental interactions when comparing bulb-size distributions. While marketable yield is important, bulb size distribution is critical for maximizing profits from Vidalia onions. Jumbo bulbs are generally more valuable than medium and colossal bulbs and are considered more desirable by growers (Ibiapina de Jesus, 2023).

In 2024, the twin-row high planting density plots also experienced significant bolting. Bolting is a complex process but can be induced by low temperatures (50-59ºF) late in the season (Mar-Apr) and enhanced by smaller bulbs (Brewster, 2008). Cool weather and smaller bulb sizes at the high planting density may help explain the increased bolting observed in the 2024 trial.

CONCLUSIONS

This study evaluated the impact of a twin-row arranged high planting density in the production of Vidalia onion in Georgia USA. We found that yield increased with planting density. Twin-row high planting density total and marketable yields were equivalent to the commercial standard planting density. Bulb size decreased as planting density increased, and the marketable size distribution also changed substantially across planting densities; twin-row planting arrangements had the highest proportion of jumbo and medium bulbs. Culls also decreased as planting density increased, and there was no difference between twin-row high and commercial standard plant populations. We also observed bolting at high planting density, but this can also be influenced by variety and cold weather. Our data indicate twin-row planting arrangements can potentially be used to increase production of high-value bulb sizes in short-day onions.

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CHAPTER 4

CONCLUSIONS

Planting arrangement and row spacing have a profound effect on plant growth and yield for vegetable crops. Narrow row planting arrangements are widely used in agronomic crops to improve production and enhance disease management; however, there is limited literature on their use in vegetable crops such as sweet corn and short-day onion, especially for the southeastern region of the United States. In this thesis, we conducted a series of trials to study the effects of narrow row planting in two major vegetable crops in Georgia using equipment readily available to growers without requiring any additional input or expertise beyond normal production practices. Additionally, these findings are particularly relevant for the southeast, which has little existing literature concerning the adaptation of agronomic techniques to vegetable crops.

In Chapter 2, we studied the effects of manipulating plant population density to optimize marketable yields by manipulating inter- and intra-row plant spacing to compare a narrow skip to the conventional row arrangements. We hypothesized that because this technique has been used successfully in field corn, and previous studies in processing sweet corn have shown an increased tolerance to crowding stress in modern sweet corn hybrids, we may see an increase in production efficiency if we adapt narrow skip row planting to sweet corn. Our results from this trial supported our hypothesis, and we found that a narrow row, 3-skip-1 planting arrangement outperformed a conventional planting arrangement for fresh market shipper sweet corn without negatively impacting the quality of ears, improving the production efficiency per area.

In Chapter 3, we also studied the effects of varying inter- and intra-row planting spaces by comparing a high planting density twin row arrangement with conventional planting styles of short day onion production. Here we hypothesized that increasing the planting density and decreasing the row spacing would result in a greater number of onions with a smaller size than under conventional settings. We found that while twin-row planting arrangements do not outperform the commercial standard planting density in terms of marketable yield, they produced a favorable bulb size distribution with a higher percentage of high-value bulbs, and that this planting arrangement has potential applications for targeting specific bulb sizes by altering the bulb size distribution to favor smaller bulbs.

To conclude, agronomic techniques for planting arrangement such as narrow or twin rows, and skip rows, can increase the yield and production efficiency of sweet corn and can be used to target smaller bulb sizes in short day onions in the southeast US. Future studies should explore if these techniques can be adapted to other vegetable crops for similar findings.