

ABSTRACT

STOKES, DONALD RAY. Generating Data-Driven Recommendations for Fundamental Soybean Agronomic Production Practices. (Under the direction of Dr. Rachel A. Vann).

In North Carolina, soybeans are planted from March to early August, resulting in various used soybean production practices, including a wide diversity of used soybean maturity groups (MG). One production practice that has historically changed with the soybean planting date (PD) is the soybean seeding rate (SR); SR increased as the PD was delayed. Current SR recommendations should be revisited as management strategies continue to evolve in the region.

In experiment one, soybean SR was evaluated to determine the optimum SR required across a wide range of PDs and soybean MGs used by North Carolina soybean producers. From 2019 to 2022, field research was conducted across North Carolina to evaluate the impact of PD (mid-March to mid-July), MG (2-7), and SR of (185,329 to 432,434 seeds ha⁻¹) on soybean stand, yield, and revenue. Planting date, MG, and SR all interacted to impact soybean yield (P=0.02) and revenue (P = 0.02). Earlier PDs, March to April 10th (day of year (DOY):80 to 100), resulted in lower yields and revenues compared to a more moderate full-season PD, April 30th - May 20th (DOY:120 to140), and delayed planting required higher agronomically optimal seeding rates (AOSR) and economically optimal seeding rates (EOSR) to maximize yield and revenue. Variations in MGs also impacted optimal SRs, with MGs (2-4) generally requiring higher AOSR and EOSR than MGs (5-8). AOSR and EOSR analyses reveal a positive correlation between SR, yield, and revenue up to a certain threshold, beyond which increasing SR does not significantly improve yield or revenue. AOSR ranged from 375,076 seeds ha⁻¹ to 432,425 seeds ha⁻¹ across PDs, while the EOSR ranged from 321,184 seeds ha⁻¹ to 432,425 seeds ha⁻¹. On average, the EOSR was 30,682 seeds ha⁻¹ lower than the AOSR when combined across

PDs, MGs, and environments.

In experiment two, the effect of soybean row spacing was evaluated. North Carolina producers plant soybeans with row spacings ranging from 7.5 inches (in) to 38 in. In the Coastal Plain region of North Carolina, which is characterized by complex crop rotations that include corn, peanuts, cotton, tobacco, and sweet potatoes, producers have planters with rippers to use on wide row spacing. Soybean producers in this region are interested in the advantages or disadvantages of using these planters to plant soybeans. From 2021 to 2022, research was conducted in the Coastal Plain region of North Carolina in five environments to determine the impact of narrow row spacings and wide row ripped spacings on plant stand, canopy closure, soil compaction, and yield.

Row spacing significantly impacted soybean stand despite targeting similar seeding rates; wide row spacings, 36 in and 38 in, resulted in lower achieved stands due to increased self-thinning within the row. Narrower row spacing, 7.5 in and 15 in, consistently exhibited 7-25% greater canopy closure than wide row spacing across environments. Penetrometer readings showed significant differences in soil penetration resistance between narrow row un-ripped and wide row ripped treatments for different soil depths at two of the four environments; however, different responses may be observed in various environments with different tillage histories. Row spacing did not significantly impact yield in three out of four environments. However, in the fourth environment, the 15 in row spacing resulted in higher yields than the 7.5 in drilled and 38 in wide row ripped treatments, suggesting a complex relationship between row spacing and environmental influences on yield outcomes.

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Generating Data-Driven Recommendations for Fundamental Soybean Agronomic Production
Practices

by
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DEDICATION

This thesis is dedicated in remembrance of my father, Donald Ray Stokes Sr., my grandparents, Freddie and Lucile Stokes, and Will and Ruth Scriven. I wish you were all here to experience this; thank you for instilling in me at an early age my love for the land and agriculture. As well as teaching me the values of hard work, the importance of being a good steward, and giving back to the community.

To my mother, Marjorie Stokes, thank you for your constant love and support, the sacrifices you have made for me, and for always pushing me to pursue my dreams. To my sister Ruthie Stokes, thank you for your constant love and for always supporting me along my journey.

BIOGRAPHY

Donald Ray Stokes Jr., son of Donald Ray Stokes Sr. and Marjorie Stokes, was born on January 23rd, 1998 in Fayetteville, North Carolina. He was raised on a fourth-generation family farm in Sampson County, North Carolina, where he developed a love for agriculture. In the spring of 2017, he graduated from Sampson Early College High School with both a high school diploma and an Associate degree in Animal Science. Following high school graduation, he attended North Carolina State University, where he graduated in the Spring of 2020 with a Bachelor of Science degree in Agriculture Science with a minor in Crop and Soil Science and Animal Science. In the fall of 2020, he started to pursue a Master of Science degree in Crop Science under Dr. Rachel A. Vann. He plans to pursue a PhD at North Carolina State University.

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CHAPTER 1

Adjusting Seeding Rate Across Soybean Planting Date and Maturity in the Southeast USA

(Metric Units)

ABSTRACT

Soybeans [*Glycine max* (L.) Merr.] are planted across a wide range of planting dates (PDs) (March to early August) in the Southeast USA, resulting in a variety of used soybean production practices. Seeding rate (SR) is one of those production practices that has historically changed with PD, with SR increasing as PD was delayed. Current SR recommendations should be revisited as management strategies evolve in the region. The objective of this study is to determine the agronomically optimum seeding rate (AOSR) and economically optimum seeding rate (EOSR) rates required for the various PDs and extensive soybean MGs used by soybean producers in the Southeast USA. The experiment was conducted across North Carolina from 2019 to 2022 across 15 environments. Main plot treatments included PD (mid-March through mid-July), sub-plot included MG (2–7), and sub-subplot included SR (185,329 to 432,434 seeds ha⁻¹). Data collection included minimum and maximum soil temperature, soil moisture, soybean days to emergence, plant stand, and yield.

Soybean days to emergence varied across PDs and environments. Generally later PDs emerged faster than earlier PDs. Planting date, MG, and SR interacted to impact soybean stand independently. Early PDs generally resulted in lower stands due to environmental conditions such as cooler soil temperatures. Slight stand reductions were observed in late PDs, likely due to hot and dry conditions. Later MGs generally had higher stands, likely due to increased disease resistance and adaptability to Southern regions. Higher seeding rates consistently led to higher stands across environments. Planting date, MG, and SR interacted to impact soybean yield (P=0.02) and revenue (P=0.02). Higher AOSR was necessary to maximize yield for MGs (2-4) compared to later MGs (5-8). As PD was delayed, higher AOSR was necessary to maximize yield across all MGs. Additionally, the AOSR was greater than the EOSR.

NOMENCLATURE

Planting date, maturity group, seeding rate, soil moisture, soil temperature, emergence, stand, yield

KEYWORDS

Soybean, Glycine max (L.) Merr

INTRODUCTION

Soybean (*Glycine max* (L.) Merr.) is a globally significant crop with a wide range of end product uses, including oil, animal feed, industrial products, and food products (USDA ERS - Oil Crops Sector at a Glance, n.d.). Given the high demand for soybeans worldwide, the United States produced 116.4 million metric tons of soy in 2022, making it the second-largest producer behind Brazil (U.S. Yield & Production, n.d.). Soybean producers in the United States play a significant role in the country's agricultural trade volume for grains, feed, and the oilseed sector (USDA ERS - Oil Crops Sector at a Glance, n.d.).

Soybeans are the largest hectare crop produced in North Carolina. In 2022, North Carolina ranked 17th among soybean-producing states in the United States, with 688,000 hectares planted and 1,632,932 million metric tons of soybean grain produced (USDA National Agricultural Statistics Service, n.d.). North Carolina currently ranks second in soybean meal usage as the state is a major producer of swine and poultry (Soybean Meal Center, 2024). Swine and poultry are the largest consumers of soybean meal in the United States (Verbeck, 2019). North Carolina currently ranks second in poultry production and third in swine production in the United States (USDA-NASS, 2020). This level of animal production creates a significant local demand for protein production, resulting in a protein deficit for North Carolina and incentivizing soybean production across the state (Piggott & Schweizer, 2018). This protein deficit has

increased soybean production in North Carolina as farmers strive to meet the demand from the swine and poultry industries. Additionally, the PD flexibility and performance across a wide range of environmental conditions make soybeans a great fit for rotational complexities in the region, further driving production (Hare et al., 2020).

Soybean PDs have been extensively researched over the years, as they are considered one of the most crucial agronomic decisions for maximizing yield (Rattalino et al., 2017). Planting date is influenced by various factors, including environmental conditions, rotational complexities, equipment availability, and producer preferences (Bateman et al., 2020; Egli & Cornelius, 2009). In North Carolina, soybeans are typically planted from March to August, with most of the planting occurring in May and June (Hare et al., 2020). The optimal planting window for full season soybeans is typically from mid-April to mid-May (Morris et al., 2021). In North Carolina, 15 to 35 percent of our hectares are double-crop soybeans planted behind wheat in mid to late June, which pushes this percent of our hectares to be planted in late planting situations (Vann et al., 2018). Depending on the environment and rotational complexity, a wide range of MGs (2–8) are used across this diverse planting window (Morris et al., 2021). In North Carolina, soybean producers use a wide range of SRs across the wide range of PDs and MGs used. Current SR recommendations vary according to PDs to ensure optimal plant stands to achieve maximum yield potential based on historical research. The historic North Carolina recommendation for final plant stand is as follows: producers should aim for a final plant stand of 185,250 seeds per ha⁻¹ for May planting; 222,300 seeds ha⁻¹ for June planting, 247,000 seeds per ha⁻¹ for July planting to ensure plant populations are not the limiting factor for yield (Dunphy, 2017; Knott et al., 2019). Historically, North Carolina SR recommendations were based on trials using determinate varieties, MG 6 or later, and focused on later PDs (Vann et al., 2021). With this wide

range of production practices used, research is needed to understand how soybean SRs should be adjusted across these production practices to maximize yield and revenue (Mengistu & Heatherly, 2006). Factors such as environmental conditions and rotational complexity can also influence the optimal SR, and understanding these dynamics can help maximize soybean yield and overall profitability.

Soybean seed is the largest input cost in production, accounting for approximately 40 percent of variable costs in soybean production (USDA ERS - Commodity Costs and Returns, n.d.). The rise in soybean seed prices can be attributed to advancements in genetics, seed treatments, herbicide traits, and other technologies (Suhre et al., 2014). The increased expense of soybean seed and evolving production practices has underlined the need to determine the AOSR, the seeding rate maximizing yield, and EOSR, the seeding rate maximizing revenue (Chen & Wiatrak, 2010).

Soybeans are plastic, thriving across diverse populations due to their branching capacity. Lower planting populations result in increased branching, pod production, and seed yield per plant (Carpenter & Board, 1997; Colet et al., 2023). Conversely, higher populations lead to taller soybean plants with fewer branches, pods, and seeds (Lindsey et al., n.d.). High plant populations are associated with quicker canopy closure, greater light interception, and lower weed competition; however, high plant populations can lead to increased competition for nutrients and water, promote lodging, and add to seed costs (Chen & Wiatrak, 2010).

Notably, studies in Iowa demonstrated comparable yields at harvest with varying plant populations, emphasizing the flexibility between SRs and soybean yield (De Bruin & Pedersen, 2008a; 2008b). In the Midwest regions of the United States, SRs have traditionally been higher than in the Southeastern regions due to slower growth driven by environmental conditions

(Gaspar et al., 2015). Studies have highlighted the variability in optimal soybean SRs, influenced by location, PD, and MG selection (Thomas et al., 2022).

Adjusting Seeding Rates Across Planting Dates

Studies conducted by Siler and Singh (2023) demonstrate the influence of PD and geographical location on the most effective SRs. While some research highlights significant interactions between PDs and SRs, others find the optimal SR to be a percentage of the rate required for maximum yield. Lee et al. (2008) discovered that for planting in May in Kentucky, the optimal plant population ranged from 108,000 to 232,000 plants per ha⁻¹ for May planting and earlier, whereas for planting in June, the optimal plant population ranged from 238,000 to 282,000 plants per ha⁻¹. Conversely, other studies conducted by Bruns (2011) and De Bruin & Pedersen (2008b) did not observe a significant interaction between PDs and SRs for PDs ranging from April to mid-June. Further studies, such as Kratochvil et al. (2004), found that a 20% reduction in SR did not significantly differ from the soybean yields achieved with standard SR 432,300 in a full season system and 555,800 seeds ha⁻¹ in a double-cropping production system respectively. In the Siler and Singh (2023) study, the SR required to maximize revenue was 63%–68% of the SR needed to maximize yield. In addition, several studies found that the smaller plant size resulting from later planting necessitates higher SRs to ensure efficient light interception (Kratochvil et al., 2004; Lee et al., 2008; Siler & Singh, 2023).

Adjusting Seeding Rates Across Maturity Groups

In addition to interactions between SR and PD, the literature also indicates an interaction between SR and MG. In the Southeastern region of the United States, a diverse range of MGs are effective in various planting situations (Boyer et al., 2015; Norsworthy & Frederick, 2002). The interaction between soybean SRs and MGs adds complexity to SR decisions. Different MGs and

even varieties within an MG respond uniquely to SRs, suggesting tailored recommendations are needed.

Thompson et al. (2015) observed that specific SRs resulted in the highest net returns for different MGs in the Mid-South region of the United States. Seeding rates of 104,000, 83,000, and 278,000 seeds per hectare on 76 cm row spacing resulted in the highest net returns for MGs 5.0, 4.0, and 3.0, respectively. Chen and Wiatrak (2011b) determined that in 2008 and 2009 for MGs 5, 7, and 8, the yield was maximized at SRs of 255,200, 228,200, and 342,500 seeds ha⁻¹, respectively. These findings suggest that the optimal SR varies for different cultivars in different MGs and may be lower than the current recommendations for MGs 4, 6, and 7 but higher for MG 8. In Arkansas, Edwards and Purcell (2005) examined a range of MGs (00–6). They reported that early MGs had a more gradual yield response to increased SR than later MGs. The response of MGs 3 and 4 to increasing SR varied and was more influenced by the variety and environmental conditions. Limited research has evaluated the interaction between PDs, MGs, and SRs in Southeastern production environments.

Understanding the interaction between PD, MGs, and SRs is crucial for optimizing soybean growth and development across various environments (Morris et al., 2021; Popp et al., 2006). As production practices evolve in the Southeast USA soybean production region, and soybean producers in this region experience a decline in specialty crop acreage and simplified rotations, soybeans are being more intensively managed; conducting further research on this interaction will provide insights for determining the most profitable SR under different planting situations. This knowledge can ultimately lead to improved productivity and profitability in the agricultural industry.

The objective of this study is to determine the AOSR and EOSR rates required for the

varied planting scenarios and extensive soybean maturity groups grown by soybean growers in the Southeast USA.

MATERIAL AND METHODS

Experimental Sites and Management

Field experiments were conducted from 2019 through 2022 across North Carolina. In 2019, the research environments included four on-farm locations: Sampson County, NC, Currituck County, NC, Union County, NC, and Yadkin County, NC. In 2020, the research environments included Rowan County, NC, and two on-farm locations in Robeson County, NC, and Beaufort County, NC. In 2021, research was conducted in Edgecombe County, NC, and at three on-farm locations in Washington County, NC, Union County, NC, and Yadkin County, NC. In 2022, research was conducted in Rowan County, NC, and three on-farm locations in Beaufort County, NC, Camden County, NC, and Johnston County, NC. Locations were selected to represent soybean growers' environmental and agronomic growing conditions in three of NC's distinct geographical regions: Coastal Plain, Tidewater, and the Piedmont region (Vann et al., 2021). The combination of year and location will be referred to as an environment (Table 1). Production and management practices followed recommendations and guidelines established by North Carolina Cooperative Extension. Research plots were 7.6m by 1.5m and were planted at a width of 38.1cm between rows using a Wintersteiger Plotseeder XXL (Table 1).

Treatment Description

The experiment was conducted as a randomized complete block design with a split-split plot arrangement. The split-split plot design consisted of the main plot factor as PD (5-8 levels), sub-plot factor as MG (7 levels), and sub-sub factor plot as SR (5 levels). Each environment consisted of four to five replications per treatment combination, depending on the available space

in each environment. Planting dates ranged from March to July for the 2019, 2021, and 2022 soybean growing seasons. In 2020, they ranged from April through July (Table 2). Maturity groups evaluated included 2,3,4,5,6,7 and 8 (Table 4). Seeding rates included 185,329, 247,105, 308,881, 370,658, and 432,434 seeds ha⁻¹. Actual SRs were adjusted to account for reported germination of the respective seed lot to achieve the targeted seeding rate.

Data Collection

The NC Climate Retrieval Observations Network of the Southeast (CRONOS) database developed by the State Climate office of NC was utilized to acquire minimum and maximum soil temperatures and soil moisture at planting (Table 2). Data was pulled from weather stations closest to each environment (Table 3). Soybean days to emergence were recorded for each PD and averaged across MGs for each environment. Soybean stand was evaluated by counting the number of plants along a meter stick placed randomly in the second and third row at the V1-V3 growth stage. Two measurements were taken per subplot, averaged, and converted into a population per hectare. After reaching physiological maturity, the plots were harvested using a Wintersteiger Quantum Pro small-plot combine; yields were adjusted to 13% moisture content.

Statistical Analysis

Plant stand, yield, and revenue data were subjected to mixed model analysis of variance using PROC GLIMMIX in SAS Version 9.4 (SAS Institute Inc., Cary, NC). A mixed model with lognormal distribution was fitted for plant stand data analysis. A heterogeneous variance model (covariance parameters varied within each environment) with lognormal distribution was fitted for yield data analysis. For economic analyses, partial revenue was estimated by multiplying yield with soybean price and subtracting seed cost. Seed cost was estimated at \$65 per 345,800 seeds ha⁻¹, and soybean price was \$16 per 67.25 kg ha⁻¹. Seed cost and price per kg ha⁻¹ were

determined based upon the values reported by the United States Department of Agriculture's national agriculture statistic services for 2022 (USDA - National Agricultural Statistics (n.d.)). For all analyses, fixed effects included PD (as day of year), MG, SR, their interactions, and quadratic forms. Random effects included environment, replication nested within the environment, PD nested within the environment, MG nested within planting date x replication x environment, and the overall error term. Degrees of freedom for all analyses were calculated using the Satterthwaite method (Littell et al., 2006).

RESULTS AND DISCUSSION

Soybean Emergence

The days to emergence varied across site years, with 2019 soybeans emerging in 26 days or less, 2020 soybeans emerging in 10 days or less, 2021 soybeans emerging in 26 days or less, and 2022 soybeans emerging in 16 days or less (Table 2). Across environments, when planting early (mid-March to early April), soybeans emerged on average in 12 days, in full season planting (late April to mid-May), soybeans emerged on average in 8 days, and when planting in June and July, soybeans also emerged on average in 8 days (Table 2). The greatest number of days to emergence was observed at the Yadkin 2019 and Yadkin 2021 environments in the earliest PD (mid-March), requiring 26 days to emergence (Table 2). Cooler soil temperatures were experienced in this environment at the time of planting. When planting before mid-May, adverse planting conditions resulting from cooler soil temperatures and increased soil moisture can cause a delay in emergence and plant stand (Muendel, 1986). Conversely, as planting is delayed, there is generally a decrease in days to emergence due to more favorable soil and air temperatures (Muendel, 1986; Stucky, 1976). The shortest days to emergence were observed at the later PDs (mid-May through mid-July) (Table 2). In these trials, seed was treated with a

fungicide and insecticide in an attempt to ensure that pest pressure did not drive differences observed across treatments.

Plant Stand

An analysis conducted across environments revealed that PD, MG, and SR significantly affected the soybean stand (Table 5). However, these factors did not interact with each other to impact the plant stand (Table 5). Since no interaction was observed between MG, PD, and SR for the plant stand, data was presented for the main effect on the soybean stand.

A quadratic response to soybean stand was observed across PDs, with the lowest stands observed at the earliest PD (Figure 1). Planting conditions during early PDs can be unfavorable due to cooler temperatures and increased moisture, leading to delayed seed emergence and a higher incidence of seedling diseases, which can ultimately reduce stand (Cox et al., 2008). This effect was observed in this study despite using seed with a fungicide seed treatment in all environments. In previous work in Kentucky, a late freeze event resulted in a 35% reduction in plant stand when planting in early March (Knott et al., 2019). In this experiment, we only observed measurable stand loss in one environment (Yadkin 21). Interestingly, the stand also declined slightly after July 9th (day of year (DOY) ~190) compared to more moderate PDs in early May due to hot and dry conditions (Figure 1). Similarly, Siler and Singh (2023) observed lower plant stands when planting in late June.

Maturity group also impacted plant stand (Table 5). Regardless of the environment, higher plant stands were achieved across PD and SR for the later MGs (≥ 5) compared to earlier MGs (2-4) (Figure 2). This could be due to the fact that these MGs are bred for production in the Southeast USA and may have more resistance to seedling diseases common to the region (Zhang et al., 2007).

Seeding rate also predictably impacted the achieved stand (Table 5). Across environments for the different PD and MG combinations, the targeted seeding rates were 185,329, 247,105, 308,881, 370,658, and 432,434 seeds ha⁻¹. Generally, we achieved 90 percent of the targeted plant stand across environments (data not shown). An increase in SR led to an increase in plant stand across PD, MG, and environments (Figure 3).

Agronomically Optimal Seeding Rate (AOSR)

In the combined analysis across environments, a three-way interaction was observed between PD, MG, and SR for yield (P=0.02) (Table 6). Data was pooled across environments to identify the best PD, MG, and SR combinations to provide soybean producers with more robust AOSR recommendations across a variety of environments and weather events. A quadratic response to AOSR was observed across the different PDs.

When planting in late March to mid-April (DOY~80 to 100), lower yields were observed compared to a more moderate full season PD in mid-May (DOY~140) (Figure 4). Similarly, Kane and Grabau (1992) reported lower yields when planting early due to smaller plants caused by cooler temperatures resulting in less canopy development. Additionally, the emergence of soybeans was delayed in late March to mid-April (DOY~80 to 100) PDs compared to later PDs, with some seeds taking up to 26 days to emerge after planting. A positive correlation was observed between SR and yield; as the SR increased, so did yield, plateauing at a moderate SR depending on MG (Table 8 and Figure 4). In mid-April and earlier (DOY 80 to 100) planting, across environments, an AOSR ranging from 375,076 to 407,665 seeds ha⁻¹ maximized yield dependent on MG, with maximum yield achieved at an AOSR of 405,331 to 406,109 seeds ha⁻¹ when employing MG 5 and 6 (Table 8 and Figure 4).

As PD was shifted to a more moderate full season PD, ranging from late April to mid-

May (DOY 120 to 140) in the Southeast USA, soybean yields were maximized. Planting from late April to mid-May (DOY 120 to 140) proved significantly more beneficial for yield compared to earlier PDs, a pattern consistent with findings from studies by Knott et al. (2019) and Morris et al. (2021). Soybeans exhibited rapid emergence, often within seven days or less after planting, as indicated in Table 2, facilitating robust vegetative growth and development, a phenomenon also noted by De Bruin & Pedersen (2008b). Similar to earlier PDs, a positive correlation between SR and yield was observed. Maturity groups (2-4) necessitated slightly higher AOSR to maximize yield compared to MGs (5-8) at late April PD (DOY~120). This is likely due to MGs (5-8) being more well-suited to growing conditions in the Southeast (Salmeron et al.,2016). In late April to mid-May (DOY 120 to 140), across environments, an AOSR ranging from 407,165 to 432,425 seeds ha⁻¹ was found to maximize yield dependent on MG, with maximum yield achieved at an AOSR of 424,390 seeds to 432,425 seeds ha⁻¹ when employing MG 5 and 6 (Table 8 and Figure 4). Similarly, Colet et al. (2023) reported optimal yields with a May PD and an AOSR of 494,200 seeds ha⁻¹, corroborating these findings (Table 8 and Figure 4).

When planting in June (DOY~160 to 180) (a double crop planting situation), higher AOSRs were needed to maximize yield compared to earlier PDs in late March to late April (DOY~80-120)(Table 8 and Figure 4). Across MGs (2-6), on June 29th (DOY 180), yield plateaued at an AOSR of 432,425 seeds per ha⁻¹. An increase in SR could not mediate the loss in yield compared to earlier PDs. Yield generally declined, similarly observed by (Nleya et al., 2020) when planting was pushed past mid-May. In June planting (DOY 160 to 180), across environments, an AOSR of 406,666 seeds ha⁻¹ to 432,425 seeds ha⁻¹ maximized yield dependent on MG (Table 8 and Figure 4). Similar results were observed by Colet et al. (2023), who

observed that an SR of 430,800 seeds ha⁻¹ was necessary to maximize soybean yield when planting in June.

In an ultra-late soybean PD, July 19th (DOY~200), more of a flat response was observed between SR and yield. Increasing SR did not drastically increase yield (Figure 4). Similar to the June PDs for MGs (2-6), yield plateaued at an AOSR of 432,425 seeds per ha⁻¹ (Table 8). This can be attributed to the reduced vegetative growth and shortened reproductive period of late-planted soybean plants (Chen & Wiatrak, 2010). Consequently, the plants were smaller with fewer nodes, and there was a decrease in light interception due to incomplete canopy closure. In July planting (DOY 200), across environments, an AOSR ranging from 406,417 to 432,425 seeds ha⁻¹ dependent on MG, with maximum yield achieved at an AOSR of 432,425 seeds ha⁻¹ when employing MG 5 and 6 (Table 8 and Figure 4).

Economically Optimal Soybean Seeding Rate (EOSR)

In the combined analysis across environments, a three-way interaction was observed between PD, MG, and SR for revenue (P=0.02) (Table 7). Data was pooled across environments to identify the best PD, MG, and SR combinations to provide soybean producers with more robust EOSR recommendations across a variety of environments and weather events. A quadratic response to EOSR was observed across the different PDs.

Early planting in late March to mid-April (DOY~80 to 100) required the lowest EOSR of all the PDs (Table 7). Lower revenue was observed compared to a full season PD in late April to mid-May (DOY~120 to 140) (Table 8 and Figure 5). Increasing SR could not mitigate the challenges associated with earlier planting, similar to those conditions observed by Siler and Singh (2023). In mid-April and earlier (DOY 80 to 100) planting, across environments, an EOSR ranging from 321,184 to 372,433 seeds ha⁻¹ maximized revenue dependent on MG, with

maximum revenue achieved at an EOSR of 372,072 to 372,433 seeds ha⁻¹ when employing MG 5 and 6 (Table 8 and Figure 5).

The highest revenue was observed as PD shifted to a more moderate full season PD in late April to mid-May (DOY~120-140) in the Southeast United States. In late April to mid-May (DOY~120 to 140), across environments, an EOSR ranging from 369,889 to 414,594 seeds ha⁻¹ maximized revenue dependent on MG, with maximum revenue achieved at an EOSR of 384,451 to 388,564 seeds ha⁻¹ when employing MG 5 and 6 on April 30th (DOY~120) (Table 8 and Figure 5). As PD was delayed to May 20th (DOY ~140), higher EOSR was needed compared to earlier April 30th (DOY~120). The EOSR varied within MGs on April 30th (DOY~120). MGs (2-4) required higher EOSR to maximize revenue than MGs (5-8). On May 20th (DOY~140), MGs (2-5) required higher EOSR to maximize revenue compared to MGs (6-8).

When planting in June or in a double crop planting situation (DOY~160-180), higher EOSRs were needed to maximize revenue compared to earlier PDs in late March to mid-April (DOY~80 to 120) (Table 8 and Figure 5). In June planting (DOY~160 to 180), across environments, an EOSR of 355,588 seeds to 432,425 seeds ha⁻¹ maximized revenue dependent on MG, with maximum revenue achieved at an EOSR of 365,492 to 398,429 seeds ha⁻¹ using MGs (6-8) (Table 8 and Figure 5). Maturity groups (2-4) required higher EOSRs to maximize revenue compared to MGs (5-8) (Table 8). Later MGs are better suited for environments in the Southeast USA (Morris et al., 2021). As planting is delayed earlier MGs have reduced vegetative growth due to limited time between emergence and entering the flowering stage in the Southeast United States (Morris et al., 2021).

In an ultra-late soybean PD, July 19th (DOY~200) required the highest EOSR to maximize revenue compared to all the PDs (Table 8 and Figure 5). Limited time between

emergence and flowering can result in decreased revenue (Mengistu & Heatherly, 2006). In July planting, across environments, an EOSR of 336,384 to 432,425 seeds ha⁻¹ maximized revenue dependent on MG combination across environments (Table 7 and Figure 5). Similar to a full season and double crop PDs, late April to late June (Day~120-180), MGs (2-4) required higher EOSRs to maximize revenue compared to MGs (5-8) (Table 8). Maximum revenue was achieved with an EOSR of 391,225 to 413,085 seeds ha⁻¹ when employing MG 5 and 6 (Table 8).

Agronomically Optimal Seeding Rate (AOSR) vs Economically Optimal Seeding Rate (EOSR)

When combined across MGs with respect to PD, the EOSR was, on average, 30,682 seeds ha⁻¹ lower than the AOSR (Table 9). Similarly observed by other studies, the AOSR is generally always higher than the EOSR (Chen and Wiatrak, 2011; Gaspar et al., 2020). As PD became delayed, reduced yields and revenue generally resulted in smaller differences between the AOSR and EOSR (Siler et al., 2023). Yield differences were variable between the PDs when combined across MGs (Table 9) The AOSR resulted in only slightly higher yields than the EOSR, on average 13 kg ha⁻¹. Conversely, the AOSR resulted in slightly lower revenue than the revenue achieved with the EOSR when combined across MG for the different PDs (Table 9). Similar to yield when combined across MGs, as PD became delayed, there was a decrease in the difference in revenue achieved between the AOSR and EOSR

When combined across PDs and averaged across MGs, the EOSR was, on average, 30,807 seeds ha⁻¹ lower than the AOSR (Table 10). Generally, there were smaller differences between the EOSR and the AOSR for earlier MGs (2-4) compared to later MGs (5-8); this is likely due to greater genetic gain in earlier MGs resulting in increased branching compacity, improved yields, and performance at lower SR (Boehm et al., 2019; Rincker et al., 2014).

CONCLUSION

Results from this study demonstrated a three-way interaction between PD, MG, and SR for both yield and revenue, highlighting the complexity of optimal SR recommendations across PDs and MGs. The AOSR and EOSR analyses demonstrate the importance of selecting appropriate PD and MG combinations, as SR cannot mitigate losses attributed to incorrect PD and MG selection. Earlier PDs, March to April 10th (day of year (DOY):80 to 100), resulted in lower yields and revenues compared to a more moderate full-season PD, April 30th - May 20th (DOY:120-140), and delayed planting required higher agronomically optimal seeding rates (AOSR) and economically optimal seeding rates (EOSR) to maximize yield and revenue. Variations in MGs also impacted optimal SRs, with MGs (2-4) generally requiring higher AOSR and EOSR than MGs (5-8). AOSR and EOSR analyses reveal a positive correlation between SR, yield, and revenue up to a certain threshold, beyond which increasing SR does not significantly improve yield or revenue. AOSR ranged from 375,076 seeds ha⁻¹ to 432,425 seeds ha⁻¹ across PDs, while the EOSR ranged from 321,184 seeds ha⁻¹ to 432,425 seeds ha⁻¹. On average, the EOSR was 30,682 seeds ha⁻¹ lower than the AOSR when combined across PDs, MGs, and environments. The EOSR was generally always lower than the AOSR. Soybean producers should evaluate these factors to make decisions that align with their economic objectives to maximize production.

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Table 1. Location, soil type, tillage, and region for each environment.

Environment	Longitude and Latitude (°N)	Soil Type	Tillage System	Region
Currituck-2019	36.388502, -76.123188	a fine, mixed, semiactive, thermic Typic Endoaquults	Conventional	Coastal Plain
Sampson-2019	35.169725182472035, -78.232312	a fine-loamy, kaolinitic, thermic Typic Kandiudults	No-Till	Coastal Plain
Union-2019	35.148330, -80.418510	a fine, mixed, semiactive, thermic Typic Hapludults	No-Till	Piedmont
Yadkin-2019	36.158747, -80.449810	a fine, kaolinitic, mesic Typic Kanhapludults.	No-Till	Piedmont
Beaufort-2020	35.6099788, -76.740680	a fine, mixed, semiactive, thermic Typic Umbraquults	Conventional	Tidewater
Robenson-2020	34.683317, -78.894190	a fine-loamy, kaolinitic, thermic Typic Kandiudults	Conventional	Coastal Plain
Rowan-2020	35.694456, -80.628234	a fine, kaolinitic, thermic Rhodic Kanhapludults	No-Till	Piedmont
Edgecombe-2021	35.891643, -77.67718	a fine-silty, siliceous, subactive, thermic Typic Paleudults, fine-loamy, siliceous, subactive, thermic Aquic Paleudults, and fine-loamy, siliceous, semiactive, thermic Typic Paleaquults	Conventional	Coastal Plain
Washington-2021	35.730719, -76.672616	a coarse-loamy, mixed, semiactive, nonacid, and thermic Typic Humaquepts	No-Till	Tidewater
Union-2021	34.861809, -80.500679	a fine, mixed, semiactive, thermic Aquic Hapludults	No-Till	Piedmont
Yadkin-2021	36.197460, -80.726720	a fine, kaolinitic, mesic Typic Kanhapludults.	No-Till	Piedmont
Beaufort-2022	35.638975, -76.720749	a fine-loamy over sandy or sandy-skeletal, mixed, semiactive, thermic Typic Umbraquults	Conventional	Tidewater
Camden-2022	36.371815, -76.158793	a fine-silty, mixed, semiactive, thermic Typic Endoaquults	Conventional	Coastal Plain
Johnston-2022	35.46267, -78.169269	a fine-loamy, siliceous, subactive, thermic Aquic Paleudults and a fine-	Conventional	Coastal Plain

Table 1
(continued)

loamy, siliceous,
semiactive, thermic Aeric
Paleaquults

Rowan-2022	35.694470, -80.629055	a fine, kaolinitic, thermic Rhodic Kanhapludults	No-Till	Piedmont
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Table 2. Minimum and Maximum soil moisture at planting, minimum and maximum soil temperature at planting, and days from planting to emergence for each planting date (PD) at each environment. Data collection locations, depths for soil temperature, and depths for soil moisture are listed in (Table 3).

	Planting Date	Minimum Soil Moisture (m3/m3)	Maximum Soil Moisture (m3/m3)	Minimum Soil Temperature (C°)	Maximum Soil Temperature (C°)	Days from Planting to Emergence
Currituck-2019	5/2/2019	0.5	0.5	21.1	25.8	7.0
	5/14/2019	0.4	0.4	19.6	23.9	7.0
	5/29/2019	0.3	0.3	26.1	32.1	9.0
	6/25/2019	0.4	0.5	25.8	29.7	10.0
	7/16/2019	0.4	0.5	27.2	29.9	9.0
	7/31/2019	0.4	0.6	25.6	29.4	8.0
Sampson-2019	3/13/2019	0.3	0.3	7.2	16.9	19.0
	3/29/2019	0.3	0.3	8.7	20.2	10.0
	4/11/2019	0.3	0.3	13.9	24.2	7.0
	5/13/2019	0.1	0.2	21.7	27.4	7.0
	5/28/2019	0.1	0.1	26.6	37.9	9.0
	6/18/2019	0.2	0.2	24.8	30.6	4.0
	7/17/2019	0.2	0.2	27.6	33.9	5.0
	7/29/2019	0.2	0.2	23.9	31.3	8.0
Union-2019	3/29/2019	0.5	0.5	9.0	17.7	13.0
	4/18/2019	0.5	0.5	17.1	23.6	12.0
	5/3/2019	0.4	0.4	21.2	28.2	7.0
	5/17/2019	0.4	0.4	19.3	28.6	5.0
	6/17/2019	0.4	0.4	24.3	33.2	10.0
	7/18/2019	0.4	0.4	28.1	35.3	4.0
	7/30/2019	0.4	0.4	24.8	33.1	13.0
Yadkin-2019	3/14/2019	0.6	0.6	8.6	13.3	26.0
	3/28/2019	-	-	6.3	13.4	14.0

	4/18/2019	0.6	0.6	16.6	21.9	12.0
	5/16/2019	0.5	0.5	17.0	26.0	13.0
	6/27/2019	0.5	0.5	23.6	29.1	12.0
Table 2 (continued)						
	7/30/2019	0.3	0.3	23.1	28.1	6.0
Beaufort-2020	4/6/2020	0.4	0.5	13.4	17.4	9.0
	4/29/2020	0.4	0.4	16.1	20.2	7.0
	5/26/2020	0.5	0.5	19.9	22.6	7.0
	6/24/20	0.5	0.5	22.8	26.4	6.0
	7/14/20	0.4	0.4	24.2	28.8	8.0
Robeson-2020	4/7/2020	0.4	0.4	17.7	20.8	6.0
	4/29/2020	0.3	0.3	19.1	21.4	8.0
	6/4/20	0.4	0.4	23.9	26.4	5.0
	6/23/20	0.4	0.4	25.6	27.4	7.0
	7/14/20	0.4	0.4	26.6	29.8	6.0
Rowan-2020	4/7/2020	0.4	0.4	13.8	17.9	9.0
	4/28/2020	0.5	0.5	12.6	18.2	8.0
	6/3/20	0.4	0.4	20.4	25.3	5.0
	6/26/20	0.4	0.4	22.1	26.0	10.0
	7/13/20	0.4	0.4	24.2	27.6	8.0
Edgecombe-2021	3/23/21	0.3	0.3	11.1	14.7	9.0
	5/3/21	0.2	0.3	19.9	23.8	4.0
	5/25/21	0.2	0.2	24.1	30.9	6.0
	6/14/21	0.3	0.3	23.2	29.8	7.0
	7/12/21	0.3	0.4	26.1	30.2	8.0
Washington-2021	3/25/21	0.2	0.2	13.5	16.0	6.0
	4/30/21	0.2	0.2	19.6	21.7	10.0
	5/20/21	0.2	0.2	20.3	24.4	6.0
	6/18/21	0.2	0.2	23.4	26.5	7.0
	7/13/21	0.2	0.2	25.0	28.5	7.0
Union-2021	3/24/21	0.2	0.2	12.8	14.7	14.0
	5/4/21	0.1	0.1	18.2	22.6	6.0

	6/16/21	0.2	0.3	23.2	26.7	8.0
	6/16/21	0.2	0.3	23.2	26.7	8.0
	7/15/21	0.2	0.2	25.2	28.8	6.0
Table 2 (continued)						
Yadkin-2021	3/24/21	0.4	0.4	12.0	14.4	26.0
	4/28/21	0.3	0.3	16.1	22.1	13.0
	6/1/21	0.3	0.3	18.7	24.4	8.0
	6/15/21	0.5	0.5	23.6	27.9	8.0
	7/14/21	0.3	0.3	24.3	28.5	7.0
Beaufort-2022	3/23/22	0.2	0.2	13.2	16.0	13.0
	4/25/22	0.2	0.2	18.2	24.2	7.0
	5/10/22	0.2	0.2	15.3	17.2	7.0
	6/15/22	0.2	0.2	24.2	29.1	5.0
	7/14/22	0.3	0.3	25.4	27.4	6.0
Camden-2022	3/22/22	0.5	0.5	11.8	16.4	13.0
	4/23/22	0.5	0.5	15.7	22.0	7.0
	5/11/22	0.5	0.5	16.9	20.8	7.0
	6/16/22	0.4	0.5	24.3	26.3	5.0
	7/5/22	0.4	0.4	24.7	29.8	6.0
Johnston- 2022	3/21/22	0.3	0.3	9.1	23.3	14.0
	4/22/22	0.3	0.3	14.8	30.3	10.0
	5/10/22	0.2	0.2	14.3	25.6	8.0
	6/23/22	0.2	0.2	24.8	33.7	7.0
	7/6/22	0.2	0.2	26.2	41.1	9.0
Rowan-2022	6/1/22	0.5	0.5	22.4	29.1	12.0
	4/26/22	0.3	0.4	17.2	20.4	6.0
	5/16/22	0.5	0.5	20.3	24.7	7.0
	7/7/22	0.3	0.6	25.6	32.2	11.0
	7/7/22	0.3	0.6	25.6	32.2	11.0

†Missing data due to soil measurement equipment not being available

Table 3. The NC climate retrieval observations network of the Southeast (CRONOS) weather station locations, depth of soil temperature readings, and depth of soil moisture readings for each environment.

Environment	Weather Station Location (Longitude, Latitude)	Soil Temperature Depth (cm)	Soil Moisture Depth (cm)
Currituck-2019	36.468581080065626, - 76.76071757815745	10	20
Sampson-2019	35.02449266335882, - 78.2826523501025	10	20
Union-2019	35.409628888775345, - 80.23556168146398	10	20
Yadkin-2019	35.696771803087266, - 80.62271831226646	10	20
Beaufort-2020	34.718830689338056, - 76.67250301207176	10	20
Robenson-2020	34.40973442069193, - 78.7910946799115	10	20
Rowan-2020	35.696771803087266, - 80.62271831226646	10	20
Edgecombe-2021	35.89373071685399, - 77.6810101803097	10	20
Washington-2021	35.87274061469522, - 76.65903340746976	10	20
Union-2021	34.968394591444834, - 79.92227449260126	10	20
Yadkin-2021	35.696771803087266, - 80.62271831226646	10	20
Beaufort-2022	35.87269714626898, - 76.65906559557415	10	20
Camden-2022	36.468581080065626, - 76.76071757815745	10	20
Johnston-2022	35.38427531257659, - 78.03454300759434	10	20
Rowan-2022	35.696771803087266, - 80.62271831226646	10	20

Table 4. Varieties planted within each maturity group (MG) each year.

Varieties used within each Maturity Group							
Year	2	3	4	5	6	7	8
2019	AG26X8	AG36X6	AG49X6	AG56X8	AG64X8	AG72X7	AG79X9
2020	AG26X8	AG36X6	AG47X9	AG56X8	AG64X8	AG72X7	AG79X9
2021	AG26XF1	AG36XF1	AG45XFO	AG56XF2	AG66F2	AG72XFO	-
2022	AG26XF1	AG36XF1	AG45XFO	AG56X8	AG64X8	AG74X8	-

‡Abbreviations: AG: Asgrow

Table 5. Summarized ANOVA results for the effects of planting date (PD), maturity group (MG), seeding rate (SR), and the relevant interactions on plant stand in a combined analysis across environments.

Type III Tests of Fixed Effects				
Effect	Num DF	Den DF	F Value	Pr > F
PD	1	691.5	26.54	<.0001
MG	1	7834	6.34	0.0118
PD*MG	1	7751	0.72	0.3972
SR_ha	1	7897	669.60	<.0001
PD*SR_ha	1	7888	0.03	0.8664
MG*SR_ha	1	7998	1.89	0.1693
PD*MG*SR_ha	1	8094	0.00	0.9683
PD*PD	1	490	22.04	<.0001
MG*MG	1	7743	35.41	<.0001
SR_ha*SR_ha	1	7669	872.97	<.0001

‡Abbreviations: PD: planting date; MG: maturity group; SR_ha: seeding rate per hectare; Num DF: numerator degrees of freedom; Den DF: denominator degrees of freedom

Table 6. Summarized ANOVA results from the effect of planting date (PD), maturity group (MG), seeding rate (SR), and the relevant interactions on soybean yield in a combined analysis across environments.

Effect	Num DF	Den DF	F Value	Pr > F
PD	1	86.99	213.51	<.0001
MG	1	2897	99.75	<.0001
SR_ha	1	6138	4.08	0.0435
PD*MG	1	2703	20.87	<.0001
PD*SR_ha	1	6157	11.09	0.0009
MG*SR_ha	1	6146	2.33	0.1270
PD*MG*SR_ha	1	6154	4.89	0.0270
PD*PD	1	73.11	463.09	<.0001
MG*MG	1	6417	1146.32	<.0001
SR_ha*SR_ha	1	6114	22.01	<.0001

†Abbreviations: PD: planting date; MG: maturity group; SR_ha: seeding rate per hectare; Num DF: numerator degrees of freedom; Den DF: denominator degrees of freedom

Table 7. Summarized ANOVA results from the effect of planting date (PD), maturity group (MG), seeding rate (SR), and the relevant interactions on partial soybean revenue in a combined analysis across environments.

Type III Tests of Fixed Effects					
Effect	Num DF	Den DF	F Value	Pr > F	
PD	1	99.65	225.41	<.0001	
MG	1	2834	92.72	<.0001	
SR_ha	1	6134	2.09	0.1483	
PD*MG	1	2645	22.80	<.0001	
PD*SR_ha	1	6153	9.13	0.0025	
MG*SR_ha	1	6142	2.73	0.0986	
PD*MG*SR_ha	1	6149	4.84	0.0279	
PD*PD	1	82.79	480.14	<.0001	
MG*MG	1	6420	1138.34	<.0001	
SR_ha*SR_ha	1	6110	19.95	<.0001	

†Abbreviations: PD: planting date; MG: maturity group; SR_ha: seeding rate per hectare; Num DF: numerator degrees of freedom; Den DF: denominator degrees of freedom

Table 8. Interpolated model with respect to seeding rate (SR) to find the seeding rate (SR) that maximizes yield and partial revenue analysis combined across environments.

DOY	M G	AOSR	Yield (kg ha ⁻¹) at AOSR	Revenue (\$ ha ⁻¹) at AOSR	EOSR	Yield (kg ha ⁻¹) at EOSR	Revenue (\$ ha ⁻¹) at EOSR	SR difference (max yield - max revenue) seeds ha ⁻¹	Yield difference (max yield - max revenue) kg ha ⁻¹	Revenue differences (max yield – max revenue) dollars per ha ⁻¹
80	2	375,076	3662	2023	321,184	3641	2036	53,892	21	-12
80	3	380,549	4282	2393	334,531	4264	2403	46,018	18	-11
80	4	386,022	4723	2655	344,331	4707	2664	41,691	16	-10
80	5	391,495	4914	2766	351,431	4898	2776	40,064	16	-9
80	6	396,968	4822	2709	356,137	4806	2718	40,831	16	-9
80	7	402,441	4463	2491	358,304	4446	2501	44,137	17	-10
80	8	407,914	3897	2149	357,300	3877	2160	50,614	20	-12
100	2	402,997	4320	2405	357,380	4302	2415	45,617	18	-11
100	3	403,775	5085	2864	365,072	5070	2873	38,703	15	-9
100	4	404,553	5647	3200	369,716	5633	3208	34,837	14	-8
100	5	405,331	5913	3360	372,072	5900	3368	33,259	13	-8
100	6	406,109	5840	3316	372,433	5827	3324	33,676	13	-8
100	7	406,887	5440	3075	370,723	5426	3084	36,164	14	-8
100	8	407,665	4780	2679	366,470	4764	2688	41,195	16	-10
120	2	430,918	4610	2566	388,199	4594	2576	42,719	17	-10
120	3	427,001	5460	3078	390,965	5446	3086	36,036	14	-8
120	4	423,084	6098	3462	390,837	6086	3470	32,247	12	-7
120	5	419,166	6424	3660	388,564	6413	3667	30,602	12	-7
120	6	415,249	6384	3637	384,451	6372	3645	30,798	12	-7
120	7	411,332	5983	3399	378,462	5970	3406	32,870	13	-8
120	8	407,415	5289	2984	370,208	5274	2993	37,207	14	-9
140	2	432,425	4446	2467	414,594	4435	2469	17,831	11	-2
140	3	432,425	5295	2976	413,091	5284	2979	19,334	11	-2
140	4	432,425	5948	3368	408,556	5936	3372	23,869	12	-4
140	5	432,425	6301	3580	401,799	6289	3587	30,626	12	-7
140	6	424,390	6296	3581	393,163	6284	3588	31,227	12	-7
140	7	415,778	5936	3368	382,645	5923	3376	33,133	13	-8
140	8	407,165	5279	2978	369,889	5264	2987	37,276	14	-9
160	2	432,425	3868	2120	432,425	3868	2120	0	0	0

160	3	432,425	4634	2579	431,092	4633	2579	1,333	1	0
Table 8 (continued)										
160	4	432,425	5235	2940	422,608	5228	2941	9,817	7	-1
160	5	432,425	5577	3145	411,579	5566	3148	20,846	11	-3
160	6	432,425	5604	3162	398,429	5591	3169	33,996	14	-8
160	7	420,223	5313	2993	383,186	5298	3001	37,037	14	-9
160	8	406,916	4753	2663	365,492	4737	2673	41,424	16	-10
180	2	432,425	3036	1621	432,425	3036	1621	0	0	0
180	3	432,425	3658	1994	432,425	3658	1994	0	0	0
180	4	432,425	4156	2293	431,445	4155	2293	980	1	0
180	5	432,425	4453	2471	416,504	4443	2472	15,921	10	-1
180	6	432,425	4500	2499	398,910	4484	2505	33,515	16	-6
180	7	424,669	4290	2377	378,735	4272	2387	45,934	18	-11
180	8	406,666	3861	2128	355,580	3841	2140	51,086	20	-12
200	2	432,425	2150	1089	432,425	2150	1089	0	0	0
200	3	432,425	2605	1362	432,425	2605	1362	0	0	0
200	4	432,425	2976	1585	431,250	2975	1585	1,175	1	0
200	5	432,425	3207	1724	413,085	3195	1725	19,340	13	-1
200	6	432,425	3260	1755	391,225	3239	1762	41,200	21	-6
200	7	429,114	3125	1676	365,825	3101	1691	63,289	25	-15
200	8	406,417	2829	1509	336,384	2802	1525	70,033	27	-16

Table 9. The seeding rate (SR) differences between the agronomically optimal seeding rate (AOSR) and economically optimal seeding rate (EOSR), the differences in the maximum achieved yield and revenue by the agronomically optimal seeding rate (AOSR) and economically optimal seeding rate (EOSR) averaged across maturity group MG with respect to planting date (PD).

DOY	SR Difference (AOSR - EOSR) seeds ha ⁻¹	Yield Difference (max yield - max revenue) kg ha ⁻¹	Revenue Difference (max yield - max revenue) dollars per ha ⁻¹
80	45,321	18	-10
100	37,636	15	-9
120	34,640	13	-8
140	27,614	12	-6
160	20,636	9	-4
180	21,062	9	-4
200	27,862	12	-6
Average	30,682	13	-7

Table 10. The seeding rate (SR) differences between the agronomically optimal seeding rate (AOSR) and economically optimal seeding rate (EOSR), the differences in the maximum achieved yield and revenue by the agronomically optimal seeding rate (AOSR) and economically optimal seeding rate (EOSR) average across planting date (PD) with respect to maturity group MG.

MG	SR Difference (AOSR - EOSR) seeds ha ⁻¹	Yield Difference (max yield - max revenue) kg ha ⁻¹	Revenue Difference (max yield - max revenue) dollars per ha ⁻¹
2	22,866	9	-5
3	20,203	8	-4
4	21,535	9	-5
5	27,237	12	-5
6	35,035	15	-7
7	41,795	16	-10
8	46,976	18	-11
Average	30,807	13	-7

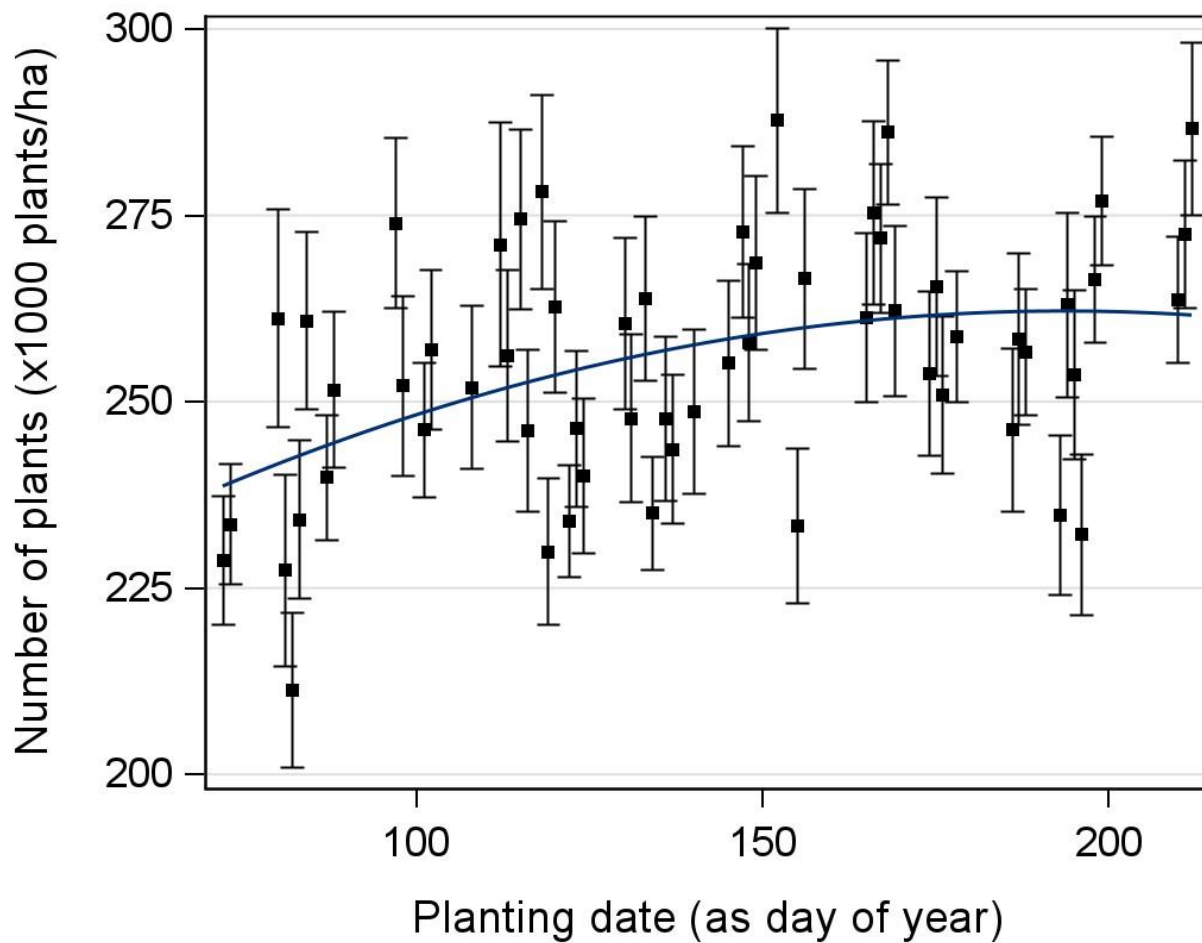


Figure 1. Effect of planting date (PD) on soybean stand combined across maturity groups (MGs), seeding rate (SR), and environments. Mean stand values combined across environments with standard error bars.

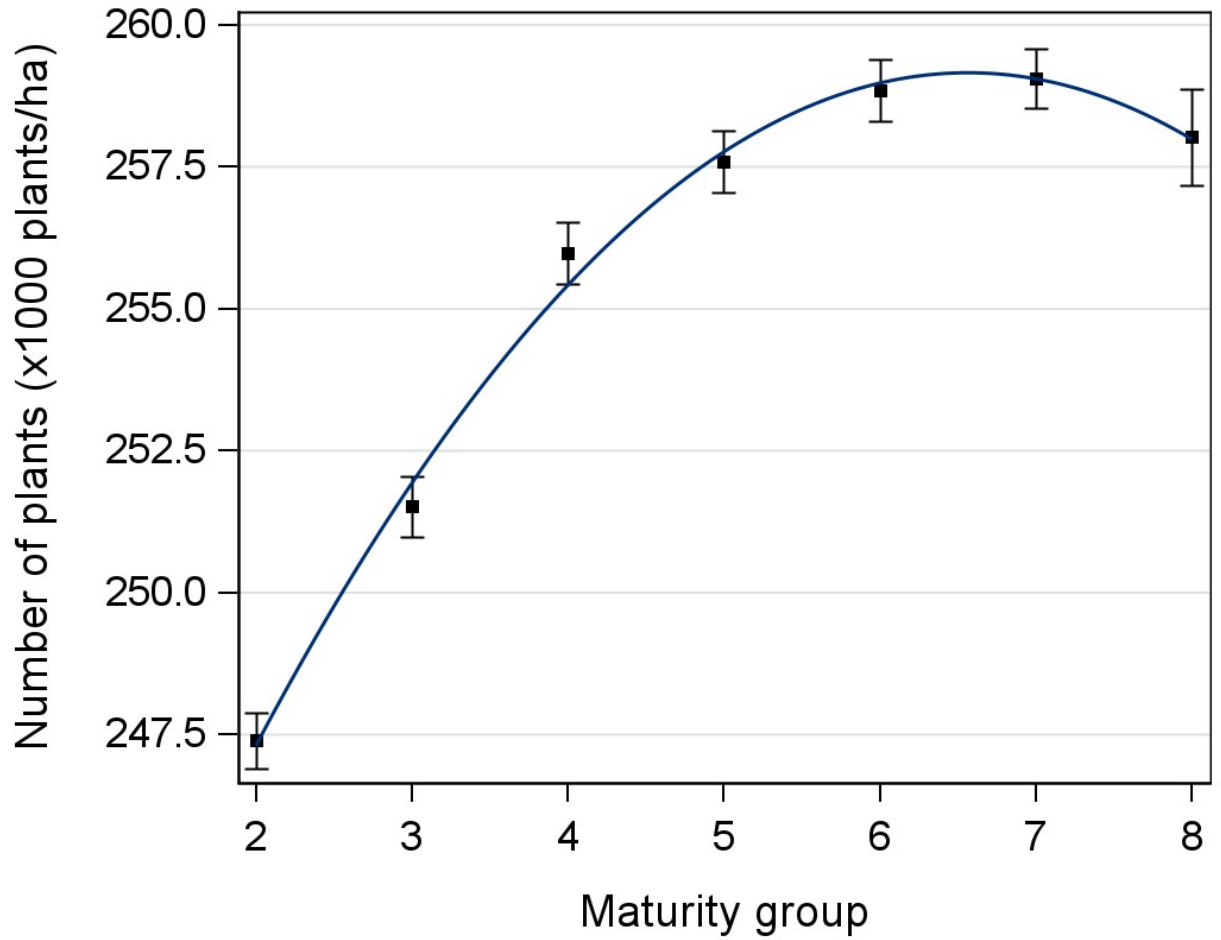


Figure 2. Effect of maturity group (MG) on plant stand combined across planting date (PD), seeding rate (SR), and environment. Mean stand values combined across environments with standard error bars.

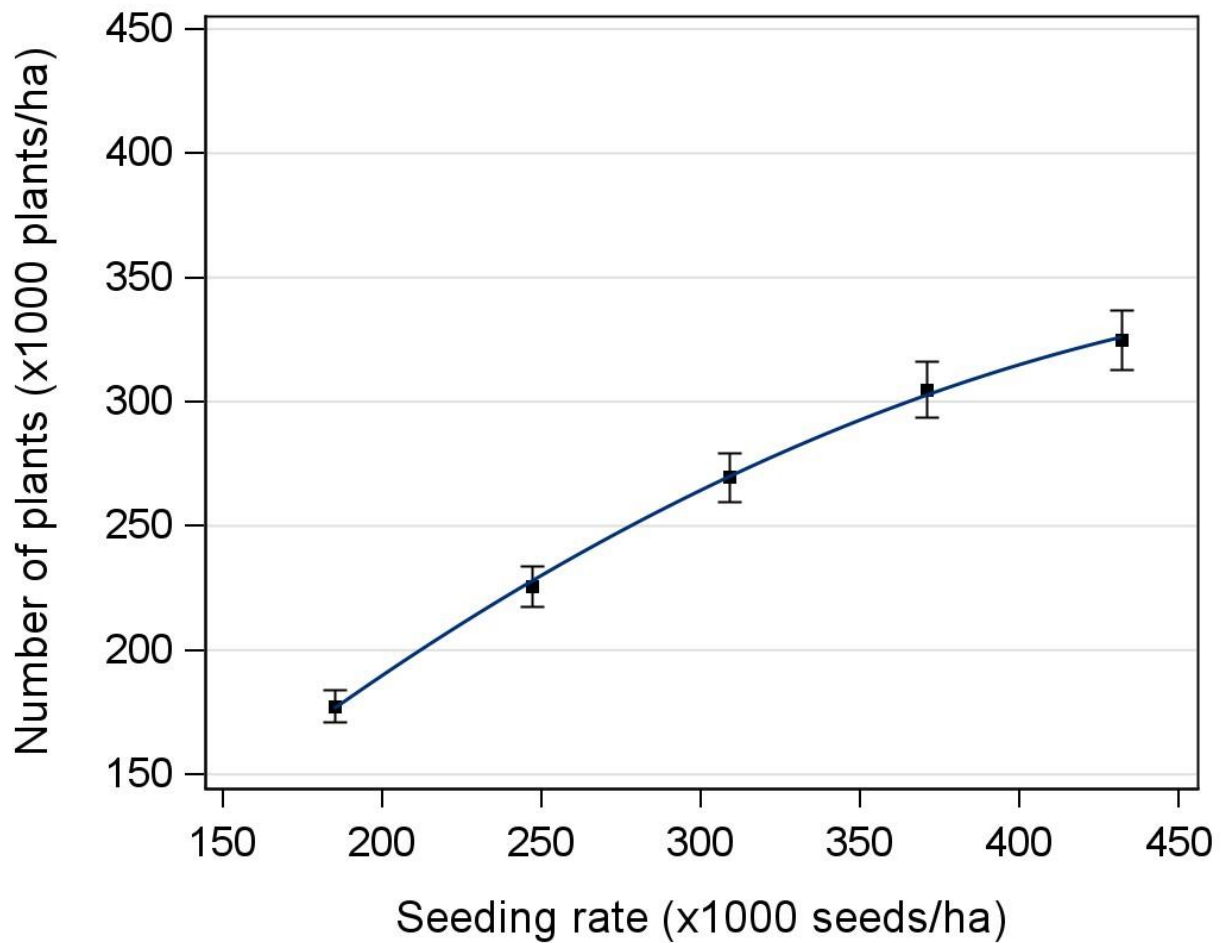


Figure 3. Effect of seeding rate (SR) on the mean of plant stand combined across planting date (PD), maturity group (MG), and environment. Mean stand values combined across environments with standard error bars.

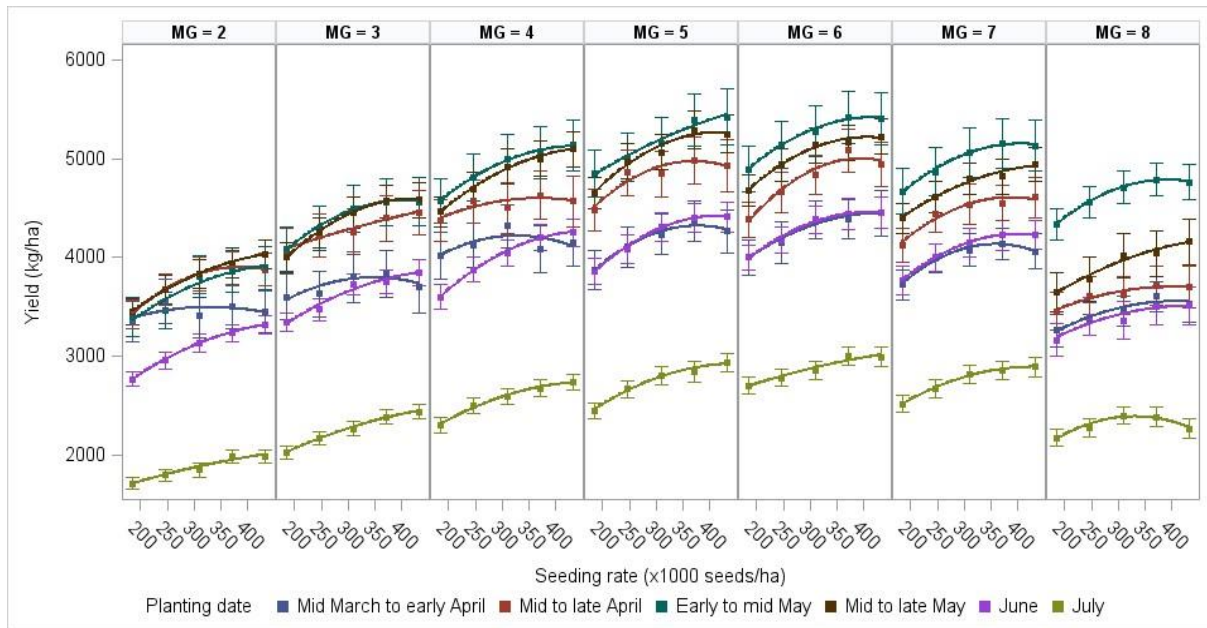


Figure 4. Interaction between planting date (PD), maturity group (MG), and seeding rate (SR) on soybean yield combined across environments. Mean yield values combined across environments with standard error bars for each planting date (PD), maturity group (MG), and seeding rate (SR) combination.

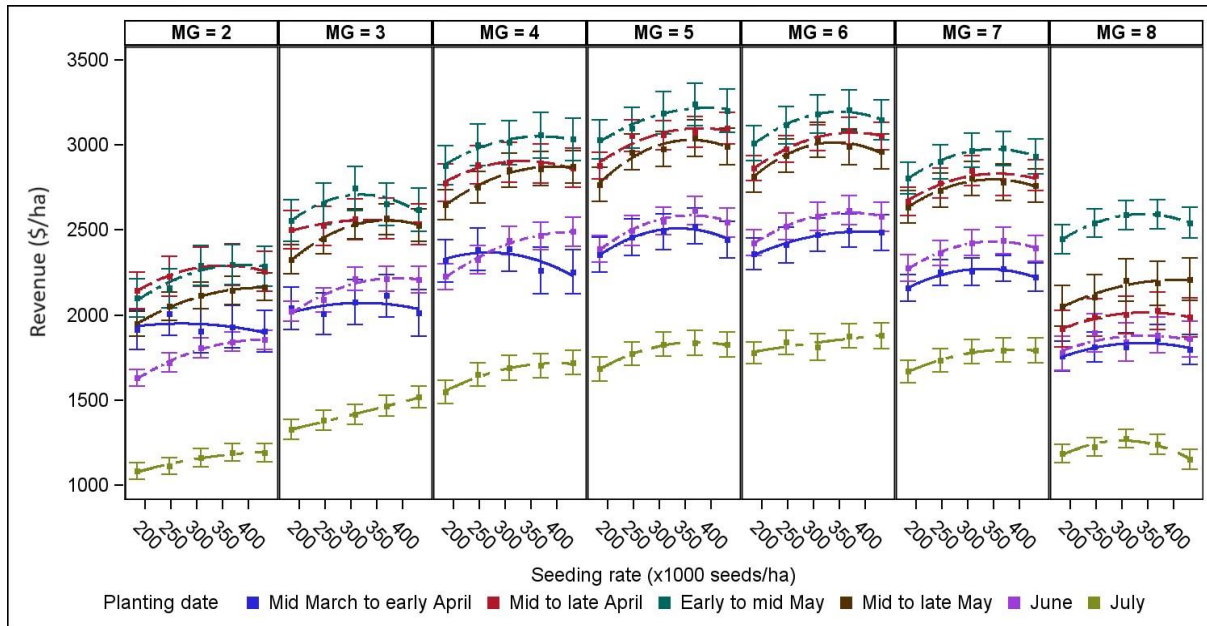


Figure 5. Interaction between planting date (PD), maturity group (MG), and seeding rate (SR) on partial revenue combined across environments. Mean revenue values combined across environments with standard error bars for each planting date (PD), maturity group (MG), and seeding rate (SR) combination.

CHAPTER 2

Implications of narrow row ow Spacing versus wide row ripped spacing on soybean production in the Coastal Plain Region of North Carolina (Standard Units)

ABSTRACT

Growers in North Carolina plant soybeans across a wide range of row spacings from 7.5 in to 38 in. Data produced on row spacing's impact on soybean yield in this environment has varied, with planting date and environmental conditions having an influence on yield response to various row spacing. Small-plot data from North Carolina often demonstrates that row spacings of less than 30 in generally yield better than wider spacings of 36 in to 38 in. However, growers in the Coastal Plain region with sandy soils express interest in the yield stability of wider rows when combined with a ripper to alleviate soil compaction. From 2021 to 2022, research was conducted in the Coastal Plain region of North Carolina in five environments to determine the impact of narrow row spacings and wide row ripped spacing on plant stand, canopy closure, soil compaction, and yield. The treatments consisted of a narrow row spacing of 15 in and a wide row ripped row spacing of 36 in and/or 38 in at all environments except one (Sampson 2022), where an additional drilled row spacing of 7.5 in was added. Data collection included soybean stand, canopy closure at flowering, soil compaction at planting, and yield at the R8 growth stage.

Despite targeting similar seeding rates, wider row spacings result in lower achieved stands due to increased self-thinning within the row. Narrow row spacing of 7.5 in and 15 in consistently exhibited 7-25% greater canopy closure compared to a wide row spacing of 36 in and 38 in row spacing across environments by beginning flowering. Yield was not significantly impacted by row spacing in three of four environments. However, the fourth environment showed that 15 in row spacing resulted in higher yields than drilled and wide-row soybeans, suggesting potential context-specific influences on yield outcomes.

NOMENCLATURE

Soybean, *Glycine max* (L.) Merr.; *Phialophora gregata*; *Heterodera glycines* Ichinohe; SCN

KEYWORDS

Narrow Row, Wide Row Ripped

INTRODUCTION

Soybean [*Glycine max* (L.) Merr.] is the largest acre row crop produced in North Carolina, contributing significantly to the state's economy annually (USDA ERS - Commodity Costs and Returns, n.d.). Soybeans are produced across a wide range of environments with many different rotational histories, soil types, and weather conditions in this state (Vann et al., 2021). Soybean producers in North Carolina also use a wide range of production practices depending on their environment and management strategies (Morris et al., 2021). Subsequently, soybean growers have a variety of row spacing options when planting their crops. These include row spacings ranging from 7.5 to 38 in, with adoption largely driven by crop rotation, equipment availability, weed control, and environmental conditions (Vann et al., 2021). Questions continually emerge about the optimal row spacing for soybeans across North Carolina due to the frequent availability of multiple row spacing options on each farm.

The unique characteristics of the Coastal Plain region, including sandy soils prone to compaction and limitations in root development, present both challenges and opportunities for soybean production (Chartres et al., 1990; Busscher et al., 2001; Mullins et al., 1994). Additionally, the Coastal Plain experiences elevated temperatures and humidity levels compared to other regions in the state, impacting soybean growth and disease susceptibility. As a result of these issues, there is growing interest in wide row ripped soybean production as a potential solution, inspired by practices common in the region for crops like peanuts, corn, and cotton

(Jordan et al., 2009).

Small-plot data available across the United States has shown that narrower soybean row spacing of 15 in or less generally optimizes soybean yield in environments assuming there are no other factors that limit yield (De Bruin & Pedersen, 2008;Thompson et al., 2015 Walker et al., 2010). The adoption of narrow row spacing across the United States is generally reflective of this. A recent analysis of 877 entries in the North Carolina Soybean Yield contest over an 18-year period indicated a shift in production practices from the use of wider row spacings of (>30 in) soybeans to a more narrow row spacing of (< 15 in) from 2002 to 2019 (Vann et al., 2021) and producer-generated data across the United States has also indicated a shift from wide rows (> 30 in) to a more narrow row spacing of (<30 in) (Andrade et al., 2019). In both analyses, researchers concluded that growers have flexibility in what row spacing is used under optimal production situations. This flexibility underscores the importance of considering various factors such as soil type, environmental conditions, management strategies, and potential yield-limiting factors when determining the most suitable row spacing for soybean planting.

Agricultural Production in the NC Coastal Plain

The Coastal Plain Region consists of over 400 soil types, resulting in a large diversity of soil types (Moreno et al., 2018). The Coastal Plain Region, which comprises of approximately 45 percent of North Carolina's total land area, forms the state's eastern boundary (Moreno et al., 2018). The lower and middle Coastal Plain soils are predominantly Ultisols, characterized by sandy surfaces and clay loam subsoils (Levi et al., 2010). These soils vary in their drainage capabilities, ranging from well-drained to naturally poorly drained soils (Joann Mossa, 1998). These soils in the middle and lower Coastal Plain Region often have low organic matter content, limited water retaining capacity, and poor fertility, thereby presenting challenges for plant

growth and development (Venuto et al., 1998).

Despite these challenges, a wide range of cash crops, such as corn, cotton, peanuts, soybeans, tobacco, and other various horticulture crops, are still produced without irrigation (Jordan et al., 2009). These crops are often produced on a wide row spacing of 36 in to 38 in. To combat the production challenges in this region, producers use a wide range of management strategies. One of the more notable management strategies is using a sub-soil shank in tandem with a planter to alleviate sub-surface soil compaction (Khalilian et al., 2017).

Soil Compaction and Ripper Technology

Soil compaction is a critical aspect of soil management and a significant contributor to land degradation (Colombi & Keller, 2019). Along with other factors, such as loss of organic matter, crusting, slaking, and hard-setting, soil compaction can lead to soil erosion, nutrient depletion, and pollution (Batey, 2009). Although soil compaction has been a long existing problem, modern farming techniques have exacerbated the problem. Developing heavy machinery, such as tractors, harvesters, and trailers, has further contributed to soil compaction. The increased use of intensive tillage practices in modern agriculture has also contributed to soil compaction (Hakansson et al., 1988; Van den Akker et al., 2003). These practices, sometimes involving frequent and deep soil plowing, can further compact the soil particles and reduce overall porosity. As a result, water infiltration and root growth are limited, leading to decreased crop productivity and increased vulnerability to erosion (Batey, 2009; McKenzie, 2001; Smart, 1998). Ripper technology can alleviate soil compaction and enhance root penetration has become important in row spacing research. Ripper technology, when combined with wider row spacing, can improve soybean root development, nutrient access, and yield, particularly in regions where soil compaction is a common issue (Djuraeva & Kuldoshev, 2022).

Soybean Yield Response to Row Spacing

The yield advantage of using narrow rows is more prominent when the time between emergence (VE) and pod set (R3) is reduced (Frederick et al., 1998; Vann et al., 2021). Implications of soybean row spacing become more pronounced in late planting situations, and early soybean maturity groups are used in early planting situations, resulting in a shortened plant growing cycle (Andrade et al., 2019). The literature has shown considerable variability in the extent of yield difference between narrow and wide row spacing. This variation has been observed across different experimental trial sites, with some instances even indicating a yield penalty associated with narrow row spacing (Hanna et al., 2008). Studies conducted by Boerma & Ashley (1982) and Bouquet (1990) demonstrated variable results from soybean row spacing; yield increases were only consistently observed with a row spacing of 20 in compared to a wide row spacing of 40 in. In contrast, research conducted by Kelley & Sweeney (2010) has shown that narrow-row soybean cropping systems have generally provided greater yield advantages in the United States' northern regions than the southern region. These findings are consistent with various studies demonstrating the higher yields and economic returns associated with narrow-row soybeans compared to wide row soybeans in various regions.

Studies conducted by De Bruin & Pedersen (2008), Walker et al. (2010), and Thompson et al. (2015) have demonstrated that utilization of narrow row spacing of 15 in for soybean planting offers numerous benefits such as enhanced crop competitiveness, quicker canopy closure, better herbicide efficacy, weed suppression, and increased seed yield when yield-limiting factors are absent. The yield response of soybeans to narrow row spacing can be affected by both abiotic and biotic stresses. Biotic factors may include pathogens, such as brown stem rot caused by *Cadophora gregata* (*Phialophora gregata*) (Grau et al., 1994). Conley et al., (2011)

proposed that soybean cyst nematode (*Heterodera glycines* Ichinohe; SCN) reduces the benefits of planting soybeans in narrow row spacing. Abiotic factors such as moisture stress can significantly reduce the yield benefit of narrow row spacing (Alessi & Power, 1982; Devlin et al., 1995). Elmore (1998) concluded that increased seeding rates in dry, low-yield potential environments have reduced yield in narrow rows.

Studies conducted in the Southeastern Coastal Plain region have also highlighted the potential benefits of integrating deep tillage practices with wide-row crop production (Chancy & Kamprath, 1982). Previous research conducted in South Carolina by Frederick et al. (1998) demonstrated that implementing deep tillage just before planting soybeans in wide rows can alleviate soil compaction, promote deep root development, and increase crop yields. Soybeans in wide rows have improved water use efficiency, increased tolerance to drought conditions, and produced higher yields under water deficit conditions (Alessi & Power, 1982; Devlin et al., 1995). Conversely, Weber et al. (1966) suggested that the advantages of narrow row spacing would be diminished in highly productive environments but enhanced in production environments characterized by high stress levels. The degree of yield variation between narrow and wide row spacing may differ depending on the experimental growing conditions. Research is needed to understand further the implications of soybean row spacing across environments with various yield-limiting factors.

Influence of Soybean Row Spacing on Plant Population and Canopy Development

Earlier canopy closure allows for soybean plants to more efficiently capture solar radiation that can influence yield (Andrade et al., 2019; Bullock et al., 1998; Salmeron et al., 2014). Canopy cover is a valuable indicator for assessing light interception and crop productivity. Optimal photosynthesis occurs when plants effectively capture and utilize

photosynthetic radiation by maximizing their canopy cover (Kandel, 2021). Narrow row spacing increases light interception, which enhances crop productivity (Singer, 2001). Increased densities of soybeans promote a faster closure of the canopy by increasing the leaf area index and light interception (Heatherly et al., 2001). Willcott et al. (1984) observed that it takes approximately 15 days longer for the canopy to close in 38 in rows compared to 10 in rows.

Row spacing also plays a pivotal role in weed competition and pest management strategies. Wide row spacing may allow for greater weed growth between rows, potentially increasing the need for additional herbicides and weed management practices (Norsworthy, 2004). Narrow rows, on the other hand, can lead to quicker canopy closure, resulting in greater shading of weed seedlings and improved competition with the crop, ultimately reducing weed pressure Forcella et al., (1992). Similarly, Yelverton and Coble (1991) observed that as row spacing decreases, the number of weeds emerging after herbicide application decreases in a linear fashion due to the increased amount of light intercepted by the soybean canopy.

The objective of this study was to evaluate the impact of soybean row spacing in sandy soil types and environments with a history of soil compaction on canopy closure and soybean yield.

MATERIAL AND METHODS

Experimental Sites and Management

Field experiments were conducted during the 2021 and 2022 soybean growing seasons in the Coastal Plain Region of North Carolina (Table 1). Locations were selected to represent agronomic and environmental conditions for soybean production in this region. In 2021, the research was conducted at the Upper Coastal Plain Research Station in Edgecombe County, NC, and the Sandhills Research Station in Montgomery County, NC. The Edgecombe location was removed from the data set due to stand issues and variability from field conditions. In 2022 the

research was conducted at the Upper Coastal Plain Research Station in Edgecombe County, the Sandhills Research Station in Montgomery County, NC, and on-farm in Sampson County, NC. The combination of year and location will be referred to as an environment (Table 1). Soil type information for each environment can be found in (Table 1). Previous management systems and tillage practices for each environment can be found in (Table 2). Management practices outside of employed treatments across environments followed recommendations and guidelines established by the North Carolina Cooperative Extension.

Treatment Description

The experiment was conducted as a randomized complete block design with 4-6 replications in each environment. The treatments consisted of a narrow row spacing of 15 in and a wide row ripped row spacing of 36 in and/or 38 in in all environments except one (Sampson 2022), where an additional 7.5 in drilled row spacing was added (Table 3). Plot size varied per environment based on row spacing (Table 3). Narrow row treatments were planted using a conventional vacuum planter and or grain drill (Figure 1). Wide row ripped treatments were planted with the use of a ripper and wide row planter pass that occurred the same day (Figures 2,3, and 4). The ripper technology consists of a cutting blade known as a coulter, which is succeeded by a slender shank referred to as a ripper (Figure 3). This agricultural implement is designed to shatter the soil to a depth ranging from 10 in to 16 in, creating a narrow opening in the ground. This opening is subsequently sealed by packing wheels or other suitable mechanisms.

In 2021, across all environments, an Asgrow AG56X8 variety was used. In 2022, an Asgrow AG 56XF2 variety was used in the Montgomery and Edgecombe environments. In 2022, in the Sampson environment, a Dyna Gro 58xt20 was used. Each of these maturities was a mid

to late maturity group 5 exhibiting a determinate growth habit.

All environments were seeded at a targeted seeding rate of 125,000 plants/A. The seeding rate was corrected for the reported germination of each variety to achieve the targeted seeding rate. In the 2021 Edgecombe environment, an issue with the planter setup and calibration resulted in a higher-than-targeted seeding rate and poor plant stand for the narrow 15 in row spacing. The Edgecombe 2021 environment was removed entirely from the data set due to environmental circumstances resulting in the poor establishment of the trial. In the Sampson 2022 environment, an issue with no-till grain drill calibration resulted in a higher-than-targeted seeding rate for the 7.5 in narrow row spacing treatment.

Data Collection

Soybean Stand

Soybean stand was evaluated by counting the number of plants along a meter stick placed randomly on the two center harvest rows at the V2 growth stage in each plot. The two measurements per plot were then averaged and converted into a population per acre.

Canopy Closure

Canopy closure was measured using the Canopeo app at the flowering growth stage. Five photos per plot were taken by holding a mobile device at a 90-degree angle above the canopy to capture quality photos. Canopeo captures images using your mobile device; this application enables users to assess the proportion of live green vegetation canopy cover in diverse agricultural crops, turfs, or grasslands (Patrignani et al., 2015). The five canopy closure readings were then averaged per plot.

Soil Compaction

At the time of planting, a total of five measurements of soil compaction were taken in

each plot across multiple depths with a Field Scout SC 900. The Field Scout SC 900 measures the level of resistance that plant roots may encounter at a depth of 0 to 18 in. Penetrometer readings were taken 2 in from seed placement row position at depths of 0 - 18 in. The penetrometer was driven at an estimated rate of 1 in per second; resistance was recorded at each increment.

Soybean Yield

After reaching soybean growth stage R8, the plots were harvested using a Wintersteiger Quantum Pro small plot combine, and yields were adjusted to 13% moisture content.

Statistical Analysis

An analysis of variance was conducted for canopy closure, yield, and compaction using PROC MIXED in SAS 9.4 (SAS Institute Cary, NC). Row spacing was evaluated as a fixed effect. Random effects included environment and replication. Degrees of freedom for all analyses were calculated using Kenward- Roger degrees of freedom. Means were separated using Fishers Protected LSD ($P=.05$)

RESULTS and DISCUSSION

Soybean Stand

Soybeans were sown at a desired seeding rate of 125,000 live seeds per acre. The desired plants per acre were achieved in the Montgomery 2021 and the Edgecombe 2022 environments. Issues with the drill setup and calibration resulted in higher plants per acre stand in the Sampson 2022 environment for the 7.5 in row spacing. We observed a reduced soybean stand in the Montgomery 2022 environment.

Row spacing had a significant impact on soybean stand in Montgomery 2021 ($P=.014$), Edgecombe 2022 ($P=.0023$), and Sampson 2022 ($P <.0001$). Despite aiming for similar seeding

rates across the various row spacings, it was observed that in most environments, the plant stand was lower with wider row spacings compared to narrower row spacings (Figure 5). The reduction in plant stand in the wider row spacing can be attributed to greater self-thinning caused by plant-to-plant competition within the row. Similarly, De Bruin, J. L., and Pedersen, P. (2008) reported that in a wide row spacing for every 100 seeds planted, only 49 plants survived until harvest when compared to a narrow row for every 100 seeds planted, 67 plants survived. Similarly, findings were reported by Ethredge et al.(1989) who observed decreased plant populations in wider row spacings. The decrease in plant stands with wider row spacing is due to the higher plant density within rows compared to narrower row spacings. In narrower rows, soybean plants face less competition for nutrients and water, which allows for better growth and development (Elmore, 1998). In contrast to these findings, Norsworthy and Shipe (2005) observed no significant differences in plant population achieved between row spacings. Interestingly, in this study, the reduction in plant stand associated with wider row spacing did not translate into a negative impact on yield as soybeans have the remarkable ability to compensate for the lower stand through enhanced resource utilization, and the plants branching compacity resulting in more nodes and pods and, ultimately, often resulting in yields comparable to those in narrower row spacings. Other studies, such as Oplinger and Philbrook (1992), suggest that lower plant stands in wider rows lead to reduced yields. These results also underscore the need for adjusting seeding rates differently across row spacings.

Canopy Closure

Row spacing had a significant impact on canopy closure at the Montgomery 2021 (0.0362), Edgecombe 2022 (0.0217), and Sampson 2022 environments ($P < 0.001$, Table 5).

Canopy closure is an important growth parameter as it is critical for soybean plants to close the

canopy before entering the reproductive growth stage to maximize light interception (Bullock et al., 1998). On average, the narrow row spacing had 7-25% greater canopy closure than the wider row spacing at the R1 growth stage (Figure 6). These findings are similar to those of Alessi and Power (1982), Arsenijevic et al. (2021), and Bertram & Pedersen (2004), who observed faster canopy closure in row spacing less than 30 in. The greater light interception in narrow row spacing can be attributed to the spatial arrangement of the plants that make up the canopy (Board & Harville, 1996). The Montgomery 2022 environment rainfall was below the 30-year average. Environmental stress and the reduction of plant stand in the narrow row treatment (Figure 5) at the V2 growth stage can be attributed to the lack of difference observed in percent canopy closure observed between the narrow row and wide row treatments as similarly observed by Wells (1991).

Early canopy closure is important for light interception, a crucial driver of photosynthesis. Singer (2001) highlighted the importance of quick canopy closure in maximizing light interception, ultimately enhancing the plants' ability to convert sunlight into energy that contributes directly to yield. Quicker canopy closure also plays a role in suppressing weed growth. By rapidly developing a dense canopy, the soybean plants outcompete weeds for light, thereby reducing weed establishment and competition (Heatherly et al., 2001)

Soil Compaction

Penetrometer readings were taken at planting across multiple soil depths. There was a significant difference in soil penetration resistance between narrow row un-ripped, and wide row ripped treatments within the tillage layers at two of the four environments at various soil depths in the soil profile (Figure 7). In the Montgomery 2021 environment, in the narrow row treatments, penetration resistance reached 2 MPa at a soil depth of 10 in (Figure 7). Other

research has shown that resistance levels of 2Mpa can limit root growth and restrict water intake (Olibone et al., 2010). At tillage depths of 7 in ($p = 0.0282$), 8 in ($p = 0.0372$), 9 in ($p = 0.0202$), and 10 in ($p = 0.0202$), the ripper resulted in reduced soil strength compared to narrow row un-ripped treatments (Figure 7). Other research has indicated that when root penetration resistance reaches 2MPa or higher, root growth could be limited, resulting in reduced yields (Martins et al., 2021). However, this was not observed in this environment. In the Sampson 2022 environment, the wide row ripped treatment reduced soil penetration resistance in the first 9 in of the soil profile; penetration resistance never exceeded root growth limiting thresholds (Table 5 and Figure 7). In the Edgecombe 2022 and Montgomery 2022 environments, soil penetration resistance was minimal for ripped and un-ripped treatments (Figure 7). Soybean response to deep tillage is dependent on soil type, weather variability, and previous tillage history (Al-Kaisi et al., 2016). All environments consisted of a history of frequent intensive deep tillage. In an environment with more diverse tillage and management practices, we might expect different responses to deep tillage on soil penetration resistance in environments with high soil strength (Peralta et al., 2021).

Soybean Yield

The soybean yield response to row spacing varied across environments (Figure 8). Row spacing did not significantly impact soybean yield in Montgomery 2021, Edgecombe 2022, and Montgomery 2022 (Table 4). In contrast, in the Sampson 2022 environment ($p = 0.0016$), 15 in row spacing outperformed drilled and wide row ripped spacing soybean yield. Others have highlighted the variable response of soybean yield to row spacing (Boerma & Ashley, 1982; Boquet et al., 1982). Across most environments, row spacing did not significantly impact soybean yield. In 2021 and 2022, temperatures were consistent with the 30-year average across

environments (data not shown). Precipitation was variable across the years. In 2021, rainfall was above the 30-year average in the Montgomery 2021 environment; however, in 2022, precipitation was very sporadic across all environments, often slightly lower than the 30-year average (data not shown). The lack of a substantial yield difference suggests that, in these environments, soybean plants can adapt to varying row spacing configurations without a significant impact on overall yield. However, row spacing performance might be different in environments with more adverse conditions.

CONCLUSION

Row spacing had a significant impact on soybean stand, with wide row spacing 36 in and 38 in often resulting in lower plant stands compared to narrow row spacings 7.5 in and 15 in. Canopy closure was significantly impacted by row spacing, with narrow row spacing 7.5 in and 15 in having 7-25% greater canopy closure than wide row spacing 36 in and 38 in at soybean flowering. Penetrometer readings showed significant differences between narrow row un-ripped, and wide row ripped treatments for different soil depths at two of the four environments. However, different responses may be observed in various environments with different tillage histories. Further research is needed to investigate the impact of deep tillage across environments with more diverse tillage histories.

Soybean yield was not significantly impacted by row spacing at three of four environments. However, in the Sampson 2022 environment, 15 in row spacing outperformed both drilled and wide row ripped spacing for soybean yield. The results suggest a complex relationship between row spacing, deep tillage, tillage history, soybean yield, and environment, suggesting that growers often have flexibility in choosing row spacing under optimal production conditions, but there are unique circumstances in the Coastal Plain where row spacing will

impact yield in optimal planting situations

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Table 1. Soil type and soil series for each environment.

Environment	Soil Type	Soil Series
Montgomery 2021	loamy, kaolinitic, thermic Arenic Kanhapludults	Ailey
Edgecombe 2022	fine-loamy, siliceous, subactive, thermic Aquic Paleudults	Coxville
Montgomery2022	loamy, kaolinitic, thermic Arenic Kanhapludults	Ailey
Sampson 2022	fine-loamy, kaolinitic, thermic Typic Kandiudults	Goldsboro

Table 2. Preceding tillage system, ripper technology use, previous crop, and rows pacing used across environments.

Environment	Tillage System	History of Ripper Technology	Preceding Crop	Row Spacing (inches)
Montgomery 2021	Conventional	Yes	Soybeans	38 in
Edgecombe 2022	Conventional	Yes	Cotton	36 in
Montgomery 2022	Conventional	Yes	Soybeans	38 in
Sampson 2022	Conventional	Yes	Corn	38 in

Table 3. Row spacing, plot dimension, and planting equipment used across environments.

Environment	Row Spacing	Plot Dimensions	Planting Equipment
Montgomery 2021	15 in (Narrow)	100 ft by 10 ft	John Deere 4 Row 7200 Narrow Row Vacuum
	38 in (Wide)	100ft by 12ft	John Deere 6 Row 7200 Vacuum with Kelly Ripper Bedder
Edgecombe 2022	15 in (Narrow)	100 ft by 10 ft	Wintersteiger Plotseed XXL John Deere 4 Row Vacuum Maxemerge with Kelly Strip-Till Ripper
	36 in (Wide)	100ft by 12ft	
Montgomery 2022	15 in (Narrow)	100 ft by 10 ft	John Deere 4 Row 7200 Narrow Row Vacuum
	38 in (Wide)	100ft by 12ft	John Deere 6 Row 7200 Vacuum with Kelly Ripper Bedder
Sampson 2022	7.5in (Drill)	100 ft by 20ft	Great Plains No-Till Drill
	15 in (Narrow)	100 ft by 10 ft	Wintersteiger Plotseed XXL
	38 in (Wide)	100ft by 12ft	John Deere 6 Row 7200 Vacuum with Inline Kelly Ripper

Table 4. Planting date, stand counts at V2, canopy closure photos at flowering, penetrometer sampling, and harvest dates across environments.

Environment	Year	Planting Date	Stand Counts V2	Canopy Closure Photos R1	Penetrometer Readings Planting	Soybean Harvest
Montgomery	2021	5/17/21	6/4/21	7/21/21	5/17/21	10/20/21
Edgecombe	2022	5/17/22	6/3/22	7/1/22	5/17/22	10/12/22
Montgomery	2022	5/10/22	6/2/22	7/18/22	5/10/22	10/20/22
Sampson	2022	5/19/22	6/5/22	7/27/22	5/19/22	10/24/22

Table 5. Summarized ANOVA results for the analysis of the effect of row spacing on soybean stand at V2, canopy closure at R1, penetrometer readings, and soybean yield in analysis by environment.

Type 3 Tests of Fixed Effects						
Effect	Dependent Variable	Environment	Num DF	Den DF	F Value	Pr > F
		Montgomery 2021	1	3	25.94	0.0146
		Edgecombe 2022	1	5.01	32.21	0.0023
		Montgomery 2022	1	2.76	0.21	0.6773
RS	Soybean Stand at V2	Sampson 2022	2	10	56.31	<.0001
		Montgomery 2021	1	3	13.11	0.0362
		Edgecombe 2022	1	4.95	10.93	0.0217
		Montgomery 2022	1	1.47	3.66	0.2395
RS	Canopy Closure at R1	Sampson 2022	2	10	58.94	<.0001
		Montgomery 2021	1	6	1	0.3559
		Edgecombe 2022	1	5	1.96	0.22
		Montgomery 2022	1	3	0.04	0.8599
RS	Penetrometer Readings Depth 0 inches	Sampson 2022	2	10	6.02	0.0192
		Montgomery 2021	1	6	2.58	0.1594
		Edgecombe 2022	1	5	0.48	0.5207
		Montgomery 2022	1	3	1.42	0.5615
RS	Penetrometer Readings Depth 1 inch	Sampson 2022	2	10	1.07	0.3802
		Montgomery 2021	1	3	2.61	0.2045
		Edgecombe 2022	1	5	0.14	0.7213
		Montgomery 2022	1	3	1.29	0.3384
RS	Penetrometer Readings Depth 2 inch	Sampson 2022	2	10	4.67	0.037
		Montgomery 2021	1	3	4.22	0.1322
		Edgecombe 2022	1	5	0.25	0.6359
		Montgomery 2022	1	3	1.87	0.265
RS	Penetrometer Readings Depth 3 inch	Sampson 2022	2	10	2.51	0.1311
RS	Penetrometer Readings Depth 4 inch	Montgomery 2021	1	3	8.06	0.0657

Table 5
(continued)

		Edgecombe 2022	1	5	0.02	0.8833
		Montgomery 2022	1	3	1.37	0.3265
		Sampson 2022	2	10	3.14	0.0874
		Montgomery 2021	1	3	2.48	0.2133
		Edgecombe 2022	1	5	0.23	0.6514
		Montgomery 2022	1	3	3.47	0.1593
RS	Penetrometer Readings Depth 5 inch	Sampson 2022	2	10	2.28	0.1532
		Montgomery 2021	1	3	5.18	0.1072
		Edgecombe 2022	1	5	1.8	0.2379
		Montgomery 2022	1	3	5.52	0.1003
RS	Penetrometer Readings Depth 6 inch	Sampson 2022	2	10	3.15	0.0871
		Montgomery 2021	1	3	15.92	0.282
		Edgecombe 2022	1	5	1.38	0.2936
		Montgomery 2022	1	3	0.8	0.4365
RS	Penetrometer Readings Depth 7 inch	Sampson 2022	2	10	8.42	0.0072
		Montgomery 2021	1	3	12.84	0.0372
		Edgecombe 2022	1	5	9.75	0.0621
		Montgomery 2022	1	3	1.16	0.3607
RS	Penetrometer Readings Depth 8 inch	Sampson 2022	2	10	4.77	0.0351
		Montgomery 2021	1	3	20.47	0.0202
		Edgecombe 2022	1	5	2.12	0.2055
		Montgomery 2022	1	3	1.62	0.2928
RS	Penetrometer Readings Depth 9 inch	Sampson 2022	2	10	3.7	0.0626
		Montgomery 2021	1	3	19.5	0.0216
		Edgecombe 2022	1	5	0.39	0.5581
		Montgomery 2022	1	3	2.13	0.2404
RS	Penetrometer Readings Depth 10 inch	Sampson 2022	2	10	1.43	0.2835
		Montgomery 2021	1	3	6.12	0.0897
RS	Penetrometer Readings Depth 11 inch	Edgecombe 2022	1	5	0.09	0.7812

Table 5 (continued)		Montgomery 2022	1	3	2.57	0.2074
			2	10	0.2	0.8212
		Sampson 2022				
		Montgomery 2021	1	3	9.4	0.0547
		Edgecombe 2022	1	5	0.01	0.9093
		Montgomery 2022	1	3	0.76	0.4469
RS	Penetrometer Readings Depth 12 inch	Sampson 2022	2	10	0.32	0.7302
		Montgomery 2021	1	3	7.97	0.0665
		Edgecombe 2022	1	5	1	0.3409
		Montgomery 2022	1	3	1.02	0.3864
RS	Penetrometer Readings Depth 13 inch	Sampson 2022	2	10	0.92	0.4295
		Montgomery 2021	1	3	5.71	0.0963
		Edgecombe 2022	-	-	-	-
		Montgomery 2022	1	3	0.13	0.7464
RS	Penetrometer Readings Depth 14 inch	Sampson 2022	2	10	0.19	0.8302
		Montgomery 2021	1	3	1.96	0.2557
		Edgecombe 2022	1	9	2.17	0.1744
		Montgomery 2022	1	1.9	0.06	0.8282
RS	Soybean Yield	Sampson 2022	2	10	13.14	0.0016

† Abbreviations: RS, row spacing



Figure 1. Narrow row John Deere 7200 vacuum planter technology.



Figure 2. Wide row John Deere 7200 vacuum planter technology.



Figure 3. Ripper technology used in front of wide row spacing treatment.



Figure 4. Narrow Row grain drill technology used.

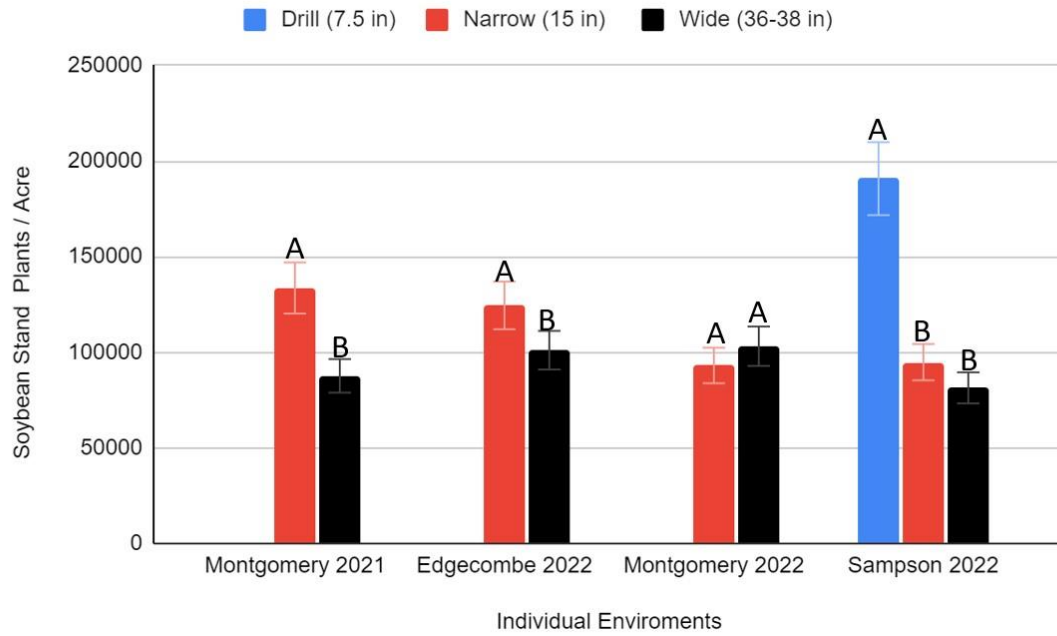
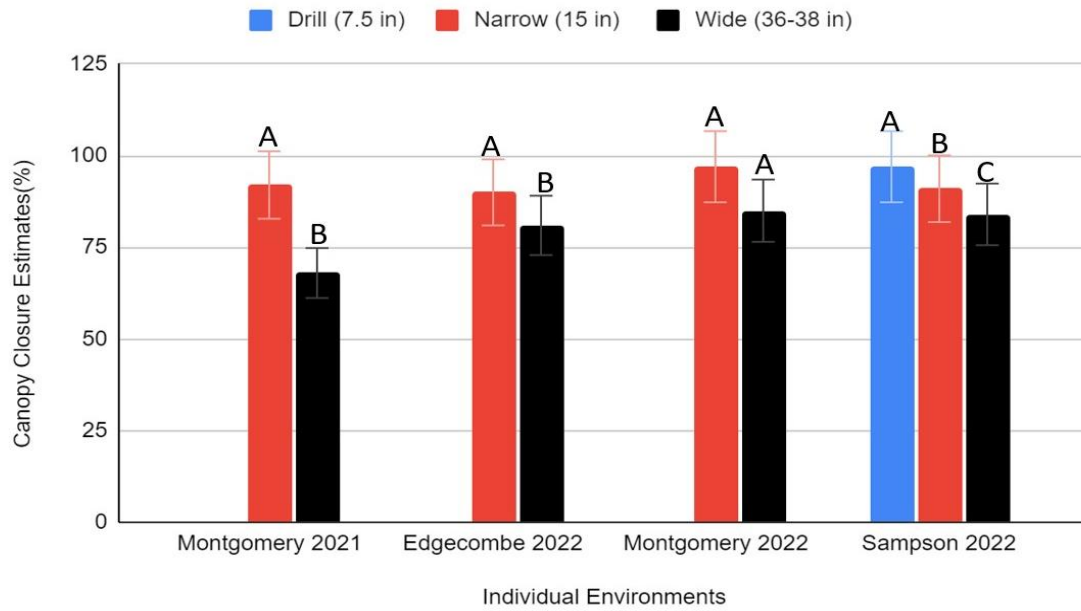
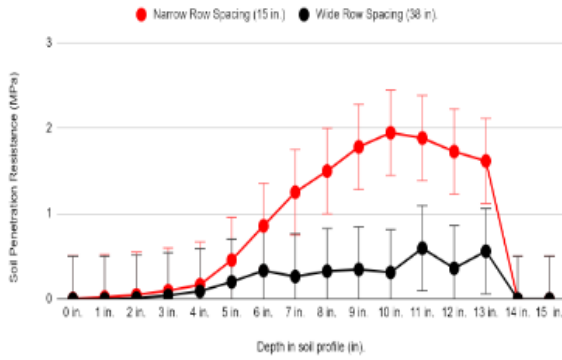


Figure 5. Row spacing impact on soybean stand achieved in each environment with standard error bars.

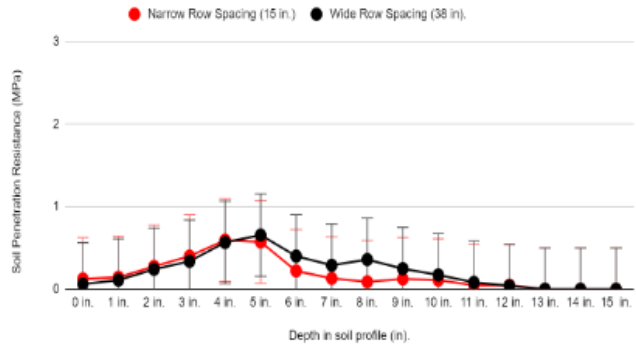


Figures 6. Row spacing impact on canopy closure estimates at flowering in each environment with standard error bars.

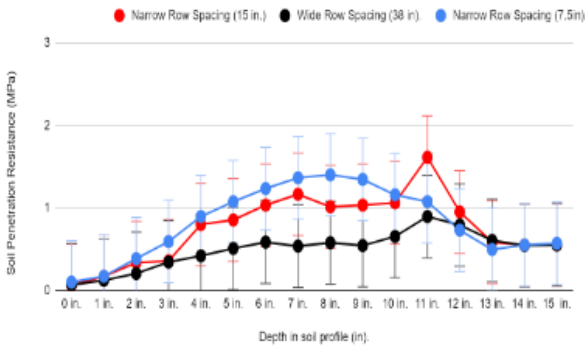
Montgomery 2021



Edgecombe 2022



Sampson 2022



Montgomery 2022

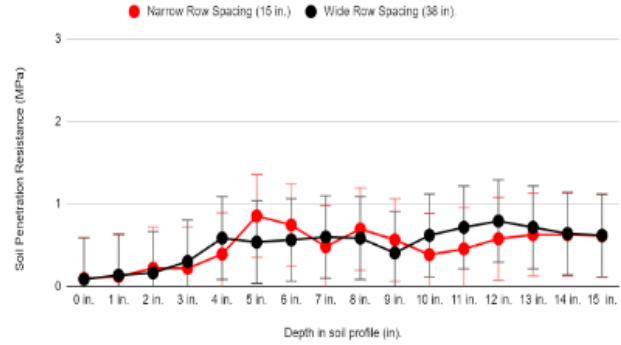


Figure 7. Row spacing impact on penetration resistance in each environment. The horizontal line represents the mean soil penetration resistance at each of the soil depth increments with standard error bars. All wide row ripped treatments received a tillage depth of 15 inches.

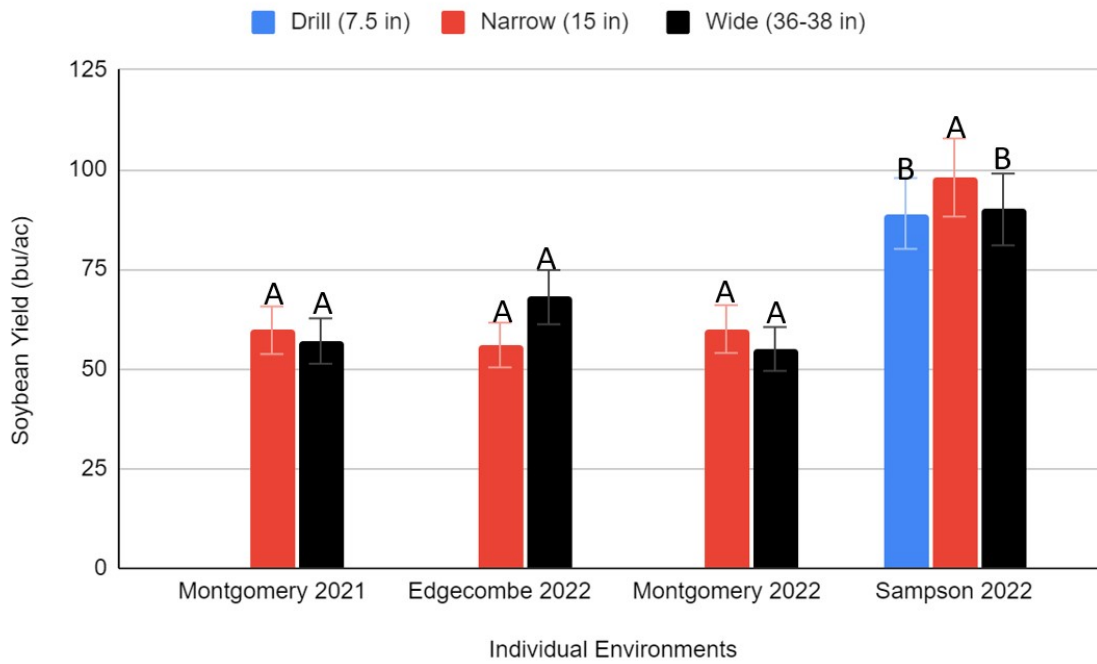


Figure 8. Row spacing impact on soybean yield in each environment with standard error bars.