ABSTRACT

CHAVEZ RESTREPO, MARCELA MARIA. Evaluating Sesame (*Sesamum indicum* L.) as an Alternative Crop for North Carolina. (Under the direction of Drs. David Suchoff and Angela Post).

Sesame (*Sesamum indicum* L.) is an important oilseed crop valuable as a food and trade commodity. Often called a survivor crop, this ancient crop tolerates drought, extreme heat, and requires minimal inputs. Sesame production in the United States was possible due to the development of non-shattering cultivars that allow for mechanical harvest. However, the country is dependent on imported sesame seed, as domestic production levels do not meet growing domestic consumption. Sesame production is limited to Texas, Oklahoma, Arizona, and southern Kansas. Though his crop was historically bred for production in the Southwestern US, declining water resources in this region pose a threat to crop production. This has generated the need to explore other suitable areas for sesame production, particularly the Southeast United States due to its warm, long growing season, and greater annual precipitation compared to the Southwest. Agronomic recommendations for this region are limited and more in-depth research is necessary to assess the crop's suitability. Therefore, we conducted three field trials and one greenhouse assay to determine sesame's suitability to North Carolina and develop agronomic recommendations for farmers seeking to produce sesame.

All field trials were conducted during the 2021 and 2022 growing seasons. In 2021, our field locations were in Clinton, Salisbury, and Jackson Springs, NC. In 2022, our field locations were Salisbury, Jackson Springs, and Plymouth, NC. The first field trial evaluated the effect of three different plant spacing treatments for the sesame variety '*ES103*' at a constant population. Data collected included early and at-harvest stand count, plant height, capsule count and seed yield. The different row spacing treatments had varying impacts on plant height and stand count

but there was no clear trend observed. Yields were not affected by row spacing, which is in agreement with previous research. The observed plasticity of this crop affords growers flexibility in the type and setting of their planting equipment.

The second field trial was a variety study. Nine sesame varieties were included in this field trial, with some varieties added or replaced in the second year. Data collected included early and at-harvest stand count, plant height, capsule count and seed yield. Yields from varieties '*S39*' and '*S3251*' in this study were comparable to those achieved in traditional sesame producing regions. Additionally, the results demonstrated that sesame production in North Carolina is feasible when using an adapted variety.

The third field trial evaluated the effect of five nitrogen fertilizer rates. Sesame variety '*ES103*' was included in this field trial at a constant population of 559,723 seeds ha^{-1}. Nitrogen was split applied at two and six weeks after planting and the data collected included at-harvest stand count, plant height, capsule count, leaf nitrogen content and seed yield. Nitrogen did not affect stand count, but had varying effects on capsule count, plant height and yield. Nitrogen application rate positively correlated with leaf nitrogen concentration, though this did not always result in increases in yield. Results indicate that nitrogen may have an effect on some growth parameters but depends on the environmental conditions.

The fourth trial investigated sesame's resistance to four root-knot nematode species in a greenhouse setting. The greenhouse assay was repeated twice and included seven sesame varieties. Findings from this study indicated that, depending on the variety, sesame may have non-host characteristics to some root-knot nematode species.

Evaluating Sesame (*Sesamum indicum* L.) as an Alternative crop for North Carolina.

by
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A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Master of Science

Crop Science

Raleigh, North Carolina
2023

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DEDICATION

To my dad, Oswaldo Chávez. I will continue making you proud. I miss you every day. To my mom, Amanda Restrepo. You are my biggest motivation. I love you. To my brothers, Daniel and Gabriel. To my wonderful husband, Ryan Ubinger. Thank you for all the love and support.

BIOGRAPHY

Marcela Chavez was born in San Pedro Sula, Honduras to Oswaldo Chávez and Amanda Restrepo. Growing up she enjoyed nature but her interest for agriculture started late in her teenage years. After completing high school, she pursued a bachelor's degree at Zamorano University, where she learned about agricultural production. Two years after completing her degree, she came to North Carolina to work at the Organic Cropping Systems lab at NC State, where she gained experience before starting her master's degree.

ACKNOWLEDGMENTS

I would like to thank Dr. David Suchoff for giving me the opportunity to work in his lab and guiding me this past years. Thank you, Dr. Angela Post for all your support and words of advice. To Dr. Adrienne Gorny for all your help in the greenhouse and sharing your knowledge in plant pathology. I would like to express my gratitude to the staff at Piedmont, Sandhills, Tidewater and Clinton Research Stations. Your help throughout the field seasons was key for this research. Special thanks to the NCDA's New and Emerging Crops Program for providing the funding for this research.

Thank you Shannon Henriquez-Inoa, this would have never been successful or possible without you! I would also like to thank Ryan Heiniger for his help throughout these years. To all the lab members at the Alternative Crops lab: Allissa Halker, Nicco Silvestri, Sam Caroll, Abby Pleasant, Ben Thompson and Abel Locklear, your hard work was greatly appreciated. To all the members at the Small Grains, Official Variety Testing and the Precision Sustainable Agriculture labs, thank you for all your help.

I would like to thank my family, whom I miss very much but their words of encouragement gave me the strength to keep going. Finally, to my husband, Ryan, for always supporting and keeping me on track through all this process.

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CHAPTER ONE

Evaluation of Sesame (*Sesamum indicum* L.) under different plant spacing

ABSTRACT

Sesame (*Sesamum indicum* L.) has a growing and unmet demand in the United States. Production is limited to the Southwest but environmental factors are creating the need to expand to other cropping regions. The Southeast may be suitable for expanded sesame production but agronomic recommendations for this region are limited and more in-depth research is necessary. Field trials were conducted across the North Carolina's small grains production regions to determine optimal row spacing. Studies were conducted in the Coastal Plains, Piedmont, Tidewater and the Jackson Springs in 2021 and 2022. Sesame variety '*ES103*' was used and three row spacing treatments (19, 38.1 and 76.2 cm) were investigated all at a plant population of 559,723 seeds ha^{-1}. Data collected included early and at harvest stand count, plant height, capsule count and seed yield. Sesame yields and capsule count did not vary across treatments for any of the locations in both years. The different row spacing treatments had varying impacts on plant height and stand count but there was no clear trend observed. In 2021, we saw no difference in early stand count in any location but in 2022 plant density was higher in the 19.0 cm spacing for two locations. Only one location observed higher plant populations in the 19.0 cm treatment 15 weeks after planting (WAP). Stand counts were variable in 2022 and highest at 19.0 and 38.2 cm spacings. Additionally, we found no difference in plant height among row spacing treatment except for taller plants in the wider spacing for one location. Our results indicate sesame yields similarly at different row spacing, affording growers flexibility in the type and settings of their planting equipment.

INTRODUCTION

Sesame (*Sesamum indicum* L.) is an important oilseed crop valuable as a food and trade commodity since ancient times (Couch et al., 2017). It is one of the oldest cultivated crops, dating back to 5,500 BC. Its popularity as an oilseed was attributed to ease of extraction and the stability of its oil (Bedigian and Harlan, 1986). Sesame oil contains lignan antioxidants that prevent oxidative rancidity, extending shelf life and making it a desirable cooking oil (Nayar and Mehra, 1970). These lignans, which belong to a group of special beneficial fibers that have cholesterol-lowering effects in humans, prevent high blood pressure and increase vitamin E in animals, are called sesamin and sesamolin. Apart from sesame lignans, sesame seed is high in protein (20-28%), vitamin B1 and is an excellent source of iron, phosphorous, copper, zinc, calcium and magnesium (Pathak et al., 2014). All these characteristics make sesame a desirable ingredient in a wide number of industries. It is used in cosmetics, pharmaceuticals, paints, lubricants, biodiesel and soap production, as well as the food industry (Ahmad et al., 2009; Morris et al., 2002; Pathak et al., 2014).

Sesame is often called a survivor crop due to its ability to grow under drought conditions and extreme heat (Langham, 2007; Langham, 2008; Sheahan, 2014). It can contribute agroecosystem services such as nematode suppression, improved soil quality by preventing nutrient leaching, reduce irrigation needs, and increase wildlife and pollinator habitat (Ashri, 1998; Bedigian & Harlan, 1986; Kamel et al., 2013; Oplinger et al., 1990). In 2021, ten countries around the world produced 77.6% of the 6.3 million tons annual global supply (FAO, 2020). The top three countries leading sesame production are Sudan (16.4%), India (11.9%) and United Republic of Tanzania (10.3%) (FAO, 2020).

In the United States, production became possible through the development of non-dehiscent cultivars that reduce shattering and allow for mechanical harvest (Langham et al., 2002). However, the country remains dependent on imported sesame seed because production levels do not meet growing domestic consumption (Gloaguen et al., 2018; Smith et al., 2000). Imports have continued to rise during the past 20 years to meet this demand (Couch et al., 2017). The United States imported 37,000 tons of sesame seed, worth $82.3 million, in 2021 (FAO STAT, 2023). This opens an opportunity for a profitable domestic market if US production can expand to meet demand. Domestic production has been limited to Texas, Oklahoma, Arizona, and southern Kansas for the past 60 years (Gloaguen et al., 2018; Grichar et al., 2011; Langham, 2007). However, declining water resources in the southwestern region caused by exceptional drought pose a threat to crop production (Grichar et al., 2011; Macdonald, 2010; Mpanga & Idowu, 2021). Despite having drought tolerance ability, sesame will perform better with more moisture (Langham, 2007).

There is a need and interest to explore other suitable areas for sesame production, particularly the southeast United States due to its warm, long growing season, and greater annual precipitation compared to the Southwest (Couch et al., 2017; Gloaguen et al., 2018). Furthermore, all commercial sesame production and harvest is fully mechanized, requiring grain planters or drills and combines (Langham, 2007). Most Southeastern grain farmers already utilize this equipment for other crops [e.g. soybean (*Glycine max* L. Merr), corn (*Zea mays* L.), and wheat (*Triticum aestivum* L.)]. Thus, barriers to adoption due to lack of equipment are non-existent. Studies support sesame's capacity to attain economically sustainable yields in this region when planting date and row spacing are optimal (Gloaguen et al., 2018).

Although sesame may have a fit in Southeastern oilseed production systems, limited research exists for the region. In the limited research, considerable variability exists regarding optimal row spacing (Couch et al., 2017). For example, Gloaguen et al. (2018) found that, depending on the cultivar, higher yields were obtained in 19 cm row spacing; however, the same authors also found no differences in yield when comparing 19 and 38.2 cm in a different location. Amabile et al. (2002) found no differences in yield using 45, 60, 75 and 90 cm spacing and so did Valiki et al. (2015) when using 40, 50, and 60 cm spacing. Additionally, the impact of row spacing on other agronomic and physiological components such as capsule count, plant height and density is nebulous. Gloaguen et al. (2018) and Lakew et al. (2018) observed taller plants with wider spacing. However, Tahir et al. (2012) found narrower spacing produced taller plants. Gloaguen et al. (2018) found no difference in capsule count between 19 and 38.2 cm spacing and Badshah et al. (2017), Filimon et al. (2018), and Lakew et al. (2018) found higher capsule counts in the wider spacing.

Many of these studies changed plant populations with row spacing such as Amabile et al. (2002), Delgado and Yermanos (1975), Gloaguen et al. (2018), and Lakew et al. (2018). For example, Gloaguen et al. (2008) used 19.0 and 38.1 cm spacing at a seeding rate of 5.6 kg ha^{-1} and used 3.4 kg ha^{-1} for their 76.2 cm spacing. Amabile et al. (2002) used 45, 60, 75 and 90 cm spacing with 3 population densities that included 80k, 100k, and 120k plants ha^{-1}. Lakew et al. (2018) tested 40, 50 and 60 cm spacing using four seeding rates (2, 3.5, 5 and 6.5 kg ha^{-1}). The change in plant population confounds the effect of row spacing on yield and other agronomic traits. No work exists comparing different row spacing while maintaining plant population constant in the Southeast. The objectives of this study were to identify appropriate row spacing

to optimize sesame yield and develop recommendations for North Carolina farmers seeking to produce sesame.

MATERIALS AND METHODS

We conducted field experiments at three locations around North Carolina in 2021: Horticultural Crops Research Station in Clinton (35°01'20.4"N, 78°16'36.1"W) on Orangeburg loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudults), Piedmont Research Station in Salisbury (35°41'56.8"N, 80°37'08.0"W) on Lloyd clay loam (fine, kaolinitic, thermic Rhodic Kanhapludults), and Sandhills Research Station in Jackson Springs (35°11'06.6"N, 9°40'52.5"W) on Candor sand (Sandy, kaolinitic, thermic Grossarenic Kandiudults). In 2022, we conducted the experiments at the Tidewater Research Station in Plymouth (35°52'17.8"N, 76°39'39.4"W) on Cape Fear loam (Fine, mixed, semiactive, thermic Typic Umbraquults), Piedmont and Jackson Springs.

We tilled the fields and sprayed for weed control (Table 1.1). In both years, we applied nitrogen approximately one week before planting and six weeks after planting, with each application consisting of 39.23 kg N ha^{-1}. The variety used for this trial was variety '*ES103'* from Equinom Ltd. (Givat Brenner, Israel) known for its late maturity and "ultra branched" characteristics.

We arranged treatments in a randomized complete block design with four blocks in all locations for both years. Plot dimensions were 1.5 m wide by 6.1 m long. We planted the experiments at a depth of 2 to 3 cm with a small plot drill (Plot Motion XL, Wintersteiger, Ried im Innkreis, Austria). In-season weed control was done with chemical applications in both years and hand weeding was done when necessary (Table 1.1). When available, the fields were irrigated a day before or after planting to achieve the soil moisture necessary for seed

germination. In Clinton, we provided irrigation two hours after planting. Plymouth was the only location with no irrigation system available and relied on rainfall. We investigated three different row spacing (RS) treatments: 19, 38.1 and 76.2 cm. We used a constant plant population of 559,723 seeds ha^{-1} for all three row spacing treatments. Consequently, seed/linear meter for each treatment was 12.20, 25.70 and 42.76 for 19, 38.1 and 76.2 cm, respectively.

Data Collection

Stand counts were collected at 2-3 and 15 weeks after planting (WAP) in both years. We counted two meters of row representative of the plot to evaluate the stand. We collected plant height and whole plant capsule count from five representative plants per plot 15 WAP. We measured plant height from the soil to the base of the apical meristem. The trials were harvested 15-21 WAP in 2021 and 16-21 WAP in 2022 with a small plot combine (Wintersteiger® Quantum Pro, Ried im Innkreis, Austria). We used glyphosate (Roundup Pro®, Bayer, Leverkusen, Germany) at 855.73 grams of acid equivalent per ha^{-1} or saflufenacil (Sharpen®, BASF The Chemical Company, Ludwigshafen, Germany) at 38.55 grams of active ingredient per ha^{-1} as harvest aids 3 to 7 days prior to harvest. Yield was calculated from each treatment plot using the total weight and moisture given by a grain gauge (HarvestMaster, Juniper Systems, Logan, UT) on the combine. When plot weights were low and the grain gauge did not provide moisture, we measured it using a grain moisture tester (DICKEY-john® Corporation GAC®2000 Grain Analysis Computer, Auburn, IL) upon returning from the field. We collected harvest samples from the combine and transported them back to the lab to measure moisture content. The samples were then placed on metal trays to air dry for 72 h or until moisture content was below 10%. When moisture content was below 10%, we cleaned each sample using a 4.76 mm round (scalper) precision and 1.98 mm triangle precision sieves (Seedburo Equipment Company, Des

Plaines, IL). We weighed the clean sample and the debris separately; moisture content was taken from each sample using a grain moisture tester.

We analyzed the data using the GLIMMIX procedure in SAS version 9.4 (SAS Institute, Cary, NC). We treated block as a random effect, considered the row spacing treatment as a fixed effect, and analyzed year and location separately. We employed least squared mean separation using Tukey's HSD adjustment at a significance of $p < 0.05$ when appropriate.

RESULTS AND DISCUSSION

Field Conditions

In the 2021 growing season, total rainfall was higher compared to the thirty-year historical averages for Clinton and Jackson Springs (Table 1.2). Precipitation was above average during June, July and August and was below average for September and October with an exception at Jackson Springs. Due to heavy rains following planting, Jackson Springs suffered seed washout, which affected stands. In Clinton, precipitation exceeded the historical average in the month of July by 17.4 cm (222%) and its total precipitation for the growing season (75.1 cm) was the highest for all locations in both years. There was no trend in annual total precipitation averaged across the state. Piedmont's total rainfall fell short of the thirty-year average and this trend was also seen in 2022 for all locations. In Clinton 2021, average monthly temperatures were consistent with the historical data except for a slightly warmer October. This same pattern is seen for this year in Jackson Springs and Piedmont. In 2022, temperatures across locations were in line with the historical data except for a slightly cooler October in Piedmont.

In Clinton 2021, we saw significant phytotoxicity due to previous herbicide trials conducted in the same field. We believe this affected sesame yields and overall crop development. Similarly, in Jackson Springs the field received S-metalochlor at planting, which

we believe affected emergence and plant height. Sesame is susceptible to many herbicides. Early applications of S-metalochlor affect plant vigor, consequently, affecting yield (Sperry et al., 2016). Knowledge of previous crop history and pesticide applications is important to avoid plant injury and consequently, yield losses (Couch et al., 2017).

Stand count

Two to Three weeks after planting

We found no differences in stand count among row spacing treatments in all locations for 2021 (Table 1.3). Stand counts for Jackson Springs in 2022 had differences among row spacing (RS) (P = 0.0132). The 19 cm (41 plants m^{-2}) RS had the highest stand counts and was different from the 38.1 (17 plants m^{-2}) and 76.2 cm treatments (25 plants m^{-2}). In Plymouth, the 19 cm (62 plants m^{-2}) had the highest stand and was different from 38.1 cm and 19 cm treatments with 38.71 and 28 plants m^{-2}, respectively (P = 0.0156, Table 1.3). We found no differences in stand count among treatments in Piedmont in 2022 (Table 1.3).

Fifteen weeks after planting

We found differences in stand count between row spacing treatments for Clinton in 2021 (P = 0.0371; Table 1.4) at 15 WAP. The 19 cm spacing had the highest density with 71 plants m^{-2} and it was different from the 38.1 (29 plants m^{-2}) and 76.2 cm (23 plants m^{-2}) treatments. There were no differences in stand count for Piedmont and Jackson Springs in 2021. For Jackson Springs in 2022, there were differences in stand count among treatments (P = 0.0002, Table 1.4). Both 38.1 (29 plants m^{-2}) and 76.2 cm (31 plants m^{-2}) were different from the 19 cm (60 plants m^{-2}) treatment. We found differences in stands between row spacing treatments for Plymouth (P = 0.0098, Table 1.4). The highest density came from the 38.1 cm (81 plants m^{-2}), which was different from both 76.2 (46 plants m^{-2}) and 19 cm (36 plants m^{-2}) treatments.

There were no differences in Piedmont 2022. These results are inconsistent and follow no trend but are in line with Gloaguen et al. (2018) who also found no differences in plant density when comparing row spacing between 19 and 38.1 cm treatments for variety *'S32'* but did find a difference in variety *'S26'* in Citra, FL. The authors found that wider spacing (38.1 cm) resulted in more plants per linear meter than the 19 cm treatment. In their Live Oak, FL location, Gloaguen et al. (2018) found the main effect of spacing impacted stands; stands were highest in the 19 and 38.1 cm compared to the 76.2 cm treatment. These results are in contrast with our findings 15 WAP in Clinton 2021 and Jackson Springs 2022, but in agreement with Plymouth 2022. Taken together, spacing treatments may affect stand counts, though we did not observe a clear trend in our trials nor in the limited published research. When comparing stands taken 2-3 WAP to 15 WAP we observe a reduction in stands in most of the locations (Table 1.3 and Table 1.4). This illustrates the crop's self-thinning ability under competition (Langham, 2007). Stands were higher at the 15 WAP mark and we believe this was due to an extended germination stage. Temperatures at planting were above the 20 °C threshold, which in many cases may delay germination (Namiki, 1995). It is important that there is adequate soil moisture during planting to achieve successful stand establishment, but rain will often move the seed deeper or create a crust in certain types of soils (Langham, 2007; Sheahan, 2014). We attest these reasons to the increase in stand counts in our locations.

Average plant height

We found differences in average plant height among the treatments in Clinton 2021 (P = 0.0048; Table 1.5). The 76.2 cm treatment had the tallest plants (29 cm), but it was not different from the 38.1 cm treatment. The RS with the shortest plants was the 19.0 cm treatment (21 cm). Similar results were reported by Gloaguen et al. (2018) where plants were taller for the 76.2 cm

treatment at a seeding rate of 3.4 kg ha^{-1} at Live Oak, FL in 2013. Lakew et al. (2018) found the widest inter-row spacing (60 cm) produced the tallest plants in a one year seeding rate study at Northeastern Ethiopia. Conversely, Tahir et al. (2012) found their narrowest spacing (15 cm) produced the tallest plants in a one-year study in Faisalabad, Pakistan. There were no differences in average plant height found in Piedmont and Jackson Springs for 2021 and all locations for 2022. Average heights in Piedmont and Jackson Springs in 2021 were 99 cm and 120 cm, respectively. In Piedmont, Jackson Springs, and Plymouth 2022 average plant heights were 125, 120, and 134 cm, respectively. These results are in agreement with Osei Bonsu (1975) where spacing treatment or different plant populations did not affect plant height. Average heights across spacing treatments ranged from 93 to 140 cm throughout all locations for both years with Clinton as the exception, where heights averaged 25.2 cm. We attribute this difference to the field conditions in this location, which included phytotoxicity and heavy rainfall (Table 1.1). Although sesame is a plastic crop and yields may not be affected by plant height (Grichar et al., 2011), this location also had the lowest yields.

Average capsule count

There were no differences in average capsule count among row spacing treatments in any of the locations for both years (Table 1.6). Average capsule count per plant across treatments ranged from 90 to 169 in all locations for both years except for Clinton in 2021 where the average was 33 capsules. Yield is related to the number of capsules per square meter (Grichar et al., 2011) and this may be the reason why yields in this location were exceptionally low. These results are in agreement with Gloaguen et al. (2018) in the Citra, FL location in 2012 and 2013 who found no difference in capsule count between 19 and 38.1 cm row spacing treatments in both varieties tested. The same authors found differences in the Live Oak, FL location for both

19 and 38.1 cm; however, the 76.2 cm treatment had more nodes with capsules than the narrower spacing. Our results disagree with Badshah et al. (2017), Filimon et al. (2018), and Lakew et al. (2018) where similar one-year studies found that the widest spacing produced higher number of nodes with capsules. Capsule count is genetically regulated by one single gene but can be highly influenced by the environment. Adequate lighting and sufficient water will help the crop express its maximum capsule per leaf axil trait (Langham, 2007). All of our locations received an adequate amount of water during the growing period of the crop with the exception of Clinton 2021 (Table 1.2).

Yield

We did not observe differences in yield for any of the locations in both years (Table 1.7). Similar results were obtained by Amabile et al. (2002) using 45, 60, 75 and 90 cm row spacing treatments in Bazile and Valiki et al. (2015) using 40, 50 and 60 cm spacing in Iran. Gloaguen et al. (2018) conducted similar row spacing trials in Citra, FL and found no differences in yield between 19 and 38.1 cm treatment in 2013 but found that the 19 cm spacing yielded higher than 38.1 cm for both varieties tested in 2012. The same authors found that row spacing had an impact on yield, depending on the variety used, concluding that at narrower spacing (19 cm) yield was higher across varieties in 2014 with the exception of one variety in 2013. Similarly, Delgado and Yermanos (1975) found higher yields in their narrowest spacing in a one year study looking at different population densities in California. Yields in our study demonstrated the crop's potential to be a successful addition to North Carolina's agronomic rotation. We saw no differences in any of the environments. Yields in Clinton 2021 averaged the lowest with 173.06 kg ha^{-1} compared to the other environments in the same year, where yields ranged from 643.05 to 720.76 kg ha^{-1}.

Due to environmental conditions and better agronomic practices, yields in 2022 were higher and ranged from 841.80 to 1,095.18 kg ha^{-1}; yield increased by 300.49 and 374.42 kg ha^{-1} in Jackson Springs and Piedmont, respectively. However, yields for our trials were still below average and we believe one of the reason for this is that the variety used was not suited for our environments in North Carolina. In variety trials conducted during the same period and locations, other varieties produced higher yields than variety *'ES103'* with a few exceptions. Yields from a five-year nursery research in Uvalde, Texas, using one variety, ranged from 1,421 to 1,808 kg ha^{-1} (Langham, 2007). A reduction in yield can occur during the drydown stage if the crop is exposed to heavy rainfall that may cause seeds to be ejected from the capsules (Gloaguen et al., 2018). Environmental conditions such as the heavy rainfall in Clinton 2021 (Table 1.2) were detrimental to the crops production potential. Sesame should yield well with 30 to 65 cm of evenly distributed precipitation throughout the growing season (Bedigian, 2011; Yingzhong, 2011).

CONCLUSION

The objectives of this row spacing study conducted in 2021 and 2022 were to identify the appropriate planting space to optimize sesame yields and develop recommendations for North Carolina growers. Though yields were below the expected average, there were no differences among the row spacing treatments. Consequently, farmers seeking to plant sesame have flexibility in the type of planting equipment as well as specific row-spacing settings. We would recommend 15 or 30 in spacing, which will allow for better weed control practices such as cultivation. Additionally, sesame will branch out in wider spacing, reducing the chance of lodging.

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Table 1.1 Chemistries used for weed control in sesame fields in 2021 and 2022.

Location	Time of application	Product name	Active Ingredient	Rate (g ai ha^{-1})
Clinton 2021	Preemergence	Roundup Original Max	Glyphosate	850.92[X]
	Postemergence	Dual Magnum	S-metolachlor	1,977.10
	Postemergence	Diuron 4L	Diuron	576.12
Sandhills 2021	Preemergence	Buccaneer Plus	Glyphosate	855.73
	At planting	Dual II Magnum	S-metolachlor	1,321.52
Sandhills 2022	Preemergence	Treflan	Trifluralin	691.90
	Postemergence	Dual II Magnum	S-metolachlor	1,321.52
Salisbury 2021	Postemergence	Diuron 4L	Diuron	576.12
	Postemergence	Roundup PowerMAX 3	Glyphosate	1,382.15
Salisbury 2022	Preemergence	Treflan 4L	Trifluralin	691.90
	Preemergence	Gramoxone SL 3.0	Paraquat	542.10
Tidewater 2022	Preemergence	Treflan 4L	Trifluralin	691.90
	Postemergence	Clethodim 2E	Clethodim	288.06

The chemistries used were subject to availability in each Research Station.
[X] Glyphosate reported in grams of acid equivalent per hectare.

Table 1.2 Average temperature and total rainfall by month during the sesame growing seasons in 2021 and 2022 at each research station.

Location	May		June		July		August		September		October		November		Total
	°C	Rainfall (cm)	°C	Rainfall (cm)	°C	Rainfall (cm)	°C	Rainfall (cm)	°C	Rainfall (cm)	°C	Rainfall (cm)	°C	Rainfall (cm)	Rainfall (cm)
Clinton															
2021	-[Y]	-	24.5	14.5	25.7	31.7	26.1	17.3	22.9	5.5	19.3	6.1	-	-	75.1
30 yr[X]	-	-	24.8	12.4	26.8	14.3	25.8	14.2	22.7	16.0	16.9	8.6	-	-	65.5
Jackson Springs															
2021	-	-	23.6	15.1	25.0	12.1	25.2	13.5	22.2	10.7	18.9	10.3	-	-	61.7
2022	-	-	24.9	7.7	26.1	10.0	24.8	9.0	21.5	13.3	15.6	1.4	-	-	41.3
30 yr	-	-	24.4	11.3	26.4	11.9	25.7	10.7	22.2	12.0	16.3	9.0	-	-	54.9
Piedmont															
2021	-	-	23.3	12.2	25.0	9.4	25.0	7.8	21.0	8.7	17.9	2.2	8.8	2.7	43.0
2022	-	-	24.4	0.8	25.7	20.7	24.1	9.4	19.8	16.1	13.3	3.1			50.0
30 yr	-	-	23.7	10.8	25.6	11.0	24.8	10.3	21.4	10.2	15.3	8.0	9.6	8.4	58.7
Plymouth											-	-	-	-	
2022	21.2	0.8	24.1	6.4	26.2	14.2	24.8	16.3	21.5	21.1	-	-	-	-	58.7
30 yr	20.2	9.8	24.4	12.6	26.4	14.8	25.6	15.8	22.8	14.9	-	-	-	-	67.9

[X] 30 year average calculated from 1990 to 2020 and collected from NOAA NCEI

[Y] Data not included for months outside the planting and harvest dates.

Weather data retrieved from the State Climate Office of North Carolina with the Cardinal Request Builder tool.

Table 1.3 Effect of row spacing on sesame stand count two to three weeks after planting in 2021 and 2022.

	Location					
	Clinton	Piedmont		Jackson Springs		Plymouth
Spacing (cm)	2021	2021	2022	2021	2022	2022
	Stand count (plants m^{-2})[Y]					
76.2	37	33	36	7	25 b [Z]	28 b
38.1	41	30	25	9	17 b	39 b
19.0	49	26	54	9	41 a	62 a
p-value	0.5773	0.6309	0.1723	0.5618	0.0132	0.0156

[Z] Means within a location and year that share a common letter are not significantly different (α=0.05).

[Y] Stand counts were calculated by dividing the data collected in the field by 0.381, 0.762 and 1.524 for 19, 38.1 and 76.2 cm, respectively, to get plants m^{-2}.

Table 1.4 Effect of row spacing on sesame stand count fifteen weeks after planting in 2021 and 2022.

	Location					
	Clinton	Piedmont		Jackson Springs		Plymouth
Spacing (cm)	2021	2021	2022	2021	2022	2022
	Stand count (plants m^{-2})[Y]					
76.2	23 b [Z]	20	26	6	31 b	46 b
38.1	29 b	27	24	5	29 b	81 a
19.0	71 a	34	56	10	60 a	36 b
p-value	0.0371	0.1174	0.1472	0.0882	0.0002	0.0098

[Z] Means within a location that share a common letter are not significantly different (α=0.05)
[Y] Stand counts were calculated by dividing the data collected in the field by 0.381, 0.762 and 1.524 for 19, 38.1 and 76.2 cm, respectively, to get plants m^{-2}.

Table 1.5 Effect of row spacing on sesame average plant height fifteen weeks after planting in 2021 and 2022.

	Location					
	Clinton	Piedmont		Jackson Springs		Plymouth
Spacing (cm)	2021	2021	2022	2021	2022	2022
	Height (cm)[Y]					
76.2	29 a[Z]	100	132	95	126	140
38.1	26 a	103	119	96	117	134
19.0	21 b	95	124	93	118	129
p-value	0.0048	0.4304	0.0571	0.8791	0.1755	0.4714

[Z] Means within a location and year that share a common letter are not significantly different (α=0.05)

[Y] Plants were measured from the soil to the base of the apical meristem.

Table 1.6 Effect of row spacing on sesame average capsule count fifteen weeks after planting in 2021 and 2022.

	Location				
	Clinton	Piedmont		Jackson Springs	
Spacing (cm)	2021	2021	2022	2021	2022
	Capsule count (capsules plant^{-1}) [X]				
76.2	57	90	123	131	169
38.1	28	136	122	108	153
19.0	15	135	167	133	117
p-value	0.0521	0.1053	0.4257	0.5999	0.5561

[X] Capsules were counted from five representative plants per treatment plot.

Table 1.7 Effect of row spacing on sesame yield in 2021 and 2022.

	Location					
	Clinton	Piedmont		Jackson Springs		Plymouth
Spacing (cm)	2021	2021	2022	2021	2022	2022
			Yield (kg ha^{-1})			
76.2	169.73	612.06	820.63	686.03	1,063.41	732.15
38.1	170.64	694.15	914.98	778.04	1,028.22	816.33
19.0	178.81	622.94	1,095.00	698.22	1,193.92	976.93
p-value	0.9849	0.9425	0.6671	0.1316	0.2268	0.6364

CHAPTER TWO

Evaluation of Sesame (*Sesamum indicum* L.) varieties for North Carolina

ABSTRACT

The development of non-dehiscent varieties that allow for mechanization made sesame (*Sesamum indicum* L.) production possible in the United. Current production is limited to the Southwest and production levels do not meet domestic demand. The Southeast is being considered for expanded sesame production but agronomic recommendations are limited for this region, necessitating more in-depth research. We conducted field trials across North Carolina's agronomic production regions to compare sesame variety performance in the Piedmont, Coastal Plains, Tidewater and Sandhills regions in 2021 and 2022. The experiment included nine sesame varieties: '*S3301*', '*S3251'*, '*S3276*', '*S39*' and '*4302*' (Sesaco Corporation, Austin, TX, USA) and '*ES103*', '*ES107'*, '*ES108*' and '*ES201*' (Equinom Ltd., Givat Brenner, Israel). We planted plots at a rate of 559,723 seeds ha^{-1} using a small plot drill. Data collected included early- and at-harvest stand count, plant height, capsule count and seed yield. The varieties performed differently in each environment and produced varying results. Sesame yields were different across varieties in all locations except two in 2021. Capsule count was different among varieties in three locations and plant height differed across varieties in two locations in 2022. Additionally, early stand counts (all locations) and at-harvest stand counts (one location) in 2021 were significantly different from one another. Results indicate variation in sesame performance across environments depending on variety. Nonetheless, yields from some varieties were equivalent to expected commercial yields in several locations, ranging from 945 to 2,608 kg ha^{-1}. These results demonstrate production potential of sesame in North Carolina.

INTRODUCTION

Sesame (*Sesamum indicum L.*) is one of the oldest domesticated oilseeds (Bedigian & Harlan, 1986). It belongs to the family of *Pedaliaceae,* which contains approximately 36 species distributed across India, Africa, Australia and the East Indies (Namiki, 1995). Two centers of origin were proposed: East Africa (Ethiopia) or Asia (Indian sub-continent or further east or Central Asia). Sesame's African origin is supported by the number of wild *Sesamum* species endemic to this area and Indian origin is supported by archeological findings of charred sesame in Pakistan that may be 5,000 years old (Ashri, 1998). Seegeler (1983) first reported the use of sesame oil in Babylon and Assyria before 2050 BC. It made its way into Brazil and later Central and South America by the Indian colonies. They brought the crop to the Unites States from Africa by the end of the 17th century (Weiss, 1971). There is evidence that Thomas Jefferson developed an interest in the crop and stated that sesame "…is among the most valuable acquisitions our country has ever made…I do not believe before that there existed so perfect substitute for olive oil." He also discussed the rule of thumb that sesame will do well where cotton (*Gossypium hirsutum* L.) does well (Betts, 1999).

Domestic production began in Texas on a limited scale during the 1950's and early 1960's (Brigham & Young, 1982, as cited in Grichar et al., 2011). This was due to the labor intense process of harvesting which consisted of cutting the sesame with a binder, shocking the stems and then feeding them into a combine when dry. Production ceased in the mid 1960's due to a change in guest worker laws that made hand labor from Mexico unavailable (Langham et al., 2002). The development of new varieties that did not require binding and could be picked up with crop lifters on a combine made production possible again in 1987. Most sesame varieties around the world are shattering varieties and require manual harvest (Grichar et al., 2011). Total

mechanization through development of non-dehiscent varieties makes sesame production in the United States unique (Couch et al., 2017). Its production has now expanded from Texas to Oklahoma, Arizona, and Kansas (Langham, 2007; Gloaguen et al., 2018; Grichar et al., 2011). However, production levels do not meet domestic consumption and sesame imports have been increasing over the years, reaching 37,000 tons worth $82.3 million in 2021 (Couch et al., 2017; FAOSTAT, 2023)

Historically, breeders have bred sesame for production in the southwestern United States, but due to the devastating droughts in this region and an increase in domestic demand, expansion to other cropping areas is critical (Mpanga & Idowu, 2021; Couch et al., 2017; Macdonald, 2010). Sesame is often called a survivor crop due to its ability to grow under drought conditions and extreme heat (Langham, 2007; Langham, 2008; Sheahan, 2014). This characteristic is associated with its large root to shoot ratio and its branched feeder root system that allows it to penetrate deep into the soil to find moisture (Langham, 2008; Oplinger et al., 1990). However, as with every crop, production is enhanced with more moisture (Langham, 2007). The Southeast may be a suitable region for sesame production because of its warm, long growing season, and greater annual precipitation compared to the Southwest (Couch et al., 2017; Gloaguen et al., 2018). Sesame production and harvest are fully mechanized, requiring grain planters or drills and combines (Langham, 2007). Southern farmers already utilize this equipment and introducing sesame into the rotation would not require additional investment (Couch et al., 2017). Sesame has rotational potential with the current agronomic crops produced in the region [e.g cotton (*Gossypium spp.* L.), corn (*Zea mays* L.), wheat (*Triticum aestivum* L.) and peanut (*Arachis hypogaea* L.)] (Langham et al., 2008). Preliminary research in this region has supports sesame's capacity to produce profitable yields when row spacing and planting date are optimal (Gloaguen

et al., 2018). Expected yields in the Southwest region range from 1,421 to 1,808 kg ha^{-1}, depending on planting date (Langham, 2007). There is limited research on which varieties will produce optimal yields in this region and many of the studies are focusing on fertility rates or planting density. For example, Gloaguen et al. (2018) utilized several sesame varieties to determine optimal planting date and row spacing in Florida. They found that, depending on the planting date and row spacing, some varieties produced higher yields. Similarly, Naim et al. (2012), in Sudan and Valiki et al. (2015), in Iran, used three varieties under different seeding densities. Hoque et al. (2007) tested three varieties and different sulfur levels. Kashani et al. (2015) tested two varieties under different nitrogen and phosphorus rates. In all of these trials, authors reported varieties yield differently depending on other factors such as environment, fertilization and agronomic management. This is because sesame germplasm has a lot of plasticity (Langham, 2007). There have been 412 different characters identified with wide variation in the world collection. The same genotype can develop differently under different conditions and different genotypes may develop differently in the same conditions (Langham, 2007). Additionally, genetics can influence other agronomic and physiological characteristics such as capsule count, plant height and in-row competition. The same researchers also found genotype variability in these characteristics. No work exists solely comparing sesame varieties in the Southeast. The objectives of this study were to identify which sesame varieties would be best suited for North Carolina's environment and generate grower recommendations for those seeking to incorporate sesame in their current production systems.

MATERIALS AND METHODS

We conducted field trials in 2021 and 2022 at research stations around North Carolina. In 2021, the fields were located at the Piedmont Research Station in Salisbury (lat. 35°41'56.8"N,

long. 80°37'08.0"W) on Lloyd clay loam (fine, kaolinitic, thermic Rhodic Kanhapludults), Horticultural Crops Research Station in Clinton (lat. 35°01'20.4"N, long. 78°16'36.1"W) on Orangeburg loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudults), and Sandhills Research Station in Jackson Springs (35°11'06.6"N 79°40'52.5"W) on Candor sand (Sandy, kaolinitic, thermic Grossarenic Kandiudults). In 2022, we conducted the experiments at the Tidewater Research Station in Plymouth (lat. 35°52'17.8"N, long. 76°39'39.4"W) on Cape Fear loam (Fine, mixed, semiactive, thermic Typic Umbraquults), Jackson Springs and Piedmont.

Prior to planting, we tilled each field and sprayed for weed control (Table 2.1). In both years, we applied nitrogen twice during the season approximately one week before planting and six weeks after planting, with each application consisting of 39.23 kg N ha^{-1}. We arranged treatments in all locations and years in a randomized complete block design with four blocks. Seed was planted using a small plot drill (Plot Motion xl, Wintersteiger, Ried im Innkreis, Austria) with seven rows spaced 19.0 cm apart. Planting depth varied based on soil moisture level and ranged between 2 to 3 cm and plot dimensions were 1.5 meters wide and 6.1 meters long.

In-season weed control was done with herbicide applications in both years and hand weeding was done when necessary (Table 2.1). When available, fields were irrigated a day before or after planting to promote seed germination. In Clinton, we provided irrigation two hours after planting. Plymouth did not have an irrigation system available and relied solely on rainfall. Two seed companies provided the varieties used for the experiment: Equinom Ltd. (Givat Brenner, Israel) and Sesaco Corporation (Austin TX, USA) (Table 2.2). Sesaco provided varieties '*S3301*', '*S3251*', '*S3276*' and '*S39*' for both years and they added variety '*4302*' for 2022. Varieties '*S39*' and '*S3301*' are single capsuled, branched and have medium-late maturity;

varieties '*S3251*' and '*S3276*' are single or single/triple capsuled, respectively, branched and have medium maturity (Table 2.2).

Equinom provided varieties '*ES103*', '*ES107*' and '*ES108*' in 2021 and for 2022 variety '*ES107*' was replaced by variety '*ES201*'. The reason for this is that variety '*ES107*' is no longer commercially available. All varieties from this company have medium maturity, except variety '*ES103*', and are triple capsuled. Variety '*ES107*' is single stemmed, while '*ES108*' and '*ES201*' are branched; variety '*ES103*' is "ultra branched" (Table 2.2). We recorded the weight of 100 seeds of each variety to keep a constant population of 559,723 seeds ha^{-1}.

Data Collection

Stand counts were collected at 2-3 and 15 weeks after planting (WAP) in both years. We counted two meters of row representative of the plot to evaluate the stand. We collected plant height and whole plant capsule count from five representative plants per plot 15 WAP. We measured plant height from the soil to the base of the apical meristem.

In 2021, the trials were harvested 15-21 WAP and 16-21 WAP in 2022 with a small plot combine (Wintersteiger® Quantum Pro, Ried im Innkreis, Austria). We used glyphosate (Roundup Pro®, Bayer, Leverkusen, Germany) at 855.73 grams of acid equivalent per ha^{-1} or saflufenacil (Sharpen®, BASF The Chemical Company, Ludwigshafen, Germany) at 38.55 grams of active ingredient per ha^{-1} as harvest aids 3 to 7 days prior to harvest. Yield was calculated from each treatment plot using the total weight and moisture given by a grain gauge (HarvestMaster, Juniper Systems, Logan, UT) on the combine. When plot weights were low and the grain gauge did not provide moisture, we measured it using a grain moisture tester (DICKEY-john® Corporation GAC2000 Grain Analysis Computer) upon returning from the field. We collected harvest samples from the combine and took them back to the lab to measure

moisture content. We air-dried the samples for 72 h or until moisture content was below 10%. We cleaned each sample using a 4.76 mm round and a 1.98 mm triangle precision sieve (Seedburo Equipment Company, Des Plaines, IL). We weight the clean sample and the debris separately and recorded moisture content using a grain moisture tester.

We analyzed the data using the GLIMMIX procedure in SAS version 9.4 (SAS Institute, Cary, NC). We treated block as a random effect, considered the row spacing treatment as a fixed effect, and analyzed year and location separately. We employed least squared mean separation using Tukey's HSD adjustment at a significance of $p < 0.05$ when appropriate.

RESULTS AND DISCUSSION

Field conditions

In the 2021 growing season, total rainfall was higher compared to the thirty-year historical averages for Clinton and Jackson Springs (Table 2.3). Precipitation was above average during June, July and August and was below average for September and October with an exception at Jackson Springs. Due to heavy rains following planting day, Jackson Springs suffered seed washout, which affected stands. In Clinton, precipitation exceeded the historical average in the month of July by 17.4 cm (222%) and its total precipitation for the growing season (75.1 cm) was the highest for all locations in both years. There was no trend in annual total precipitation averaged across the state. Piedmont's total rainfall fell short of the thirty-year average and this trend was seen in 2022 for all locations. In Clinton 2021, average monthly temperatures were consistent with the historical data except for a slightly warmer October. This same pattern is seen for this year in Jackson Springs and Piedmont. In 2022, temperatures across locations were in line with the historical data except for a slightly cooler October in Piedmont.

In Clinton 2021, we saw significant phytotoxicity due to previous herbicide trials conducted in the same field. We believe this affected sesame yields and overall crop development. Similarly, in Jackson Springs the field received S-metalochlor at planting, which we believe affected emergence and plant height. Sesame is susceptible to many herbicides. Early applications of S-metalochlor affect plant vigor, consequently, affecting yield (Sperry et al., 2016). Knowledge of previous crop history and pesticide applications is important to avoid plant injury and consequently, yield losses (Couch et al., 2017).

Stand count

Two to Three weeks after planting

We found differences in stand count among varieties in all locations for 2021 (Table 2.4). In Clinton, variety '*ES107*' had the highest number of emerged plants with 68 plants m^{-2} but it was not different from varieties '*ES108'*, '*S3251*', '*S3301*', '*ES103*' and '*S39*'; stand counts ranged from 53 to 68 plants m^{-2} ($P = 0.0348$). The variety with the lowest stand counts was '*S3276*' (43 plants m^{-2}) and was not different from varieties '*S3301*', '*ES103*', and '*S39*'; stand counts ranged from 43 to 59 plants m^{-2}. In Piedmont, variety '*S3251*' (41 plants m^{-2}) had the highest stand and was not different from varieties '*ES108*', '*ES10*3', '*S39*' and '*S3276*'; stand counts ranged from 34 to 41 plants m^{-2} ($P = 0.0186$). Variety '*ES107*' (18 plants m^{-2}) had the lowest density and was not different from variety '*S3301*' (24 plants m^{-2}). In Jackson Springs, the variety that had the highest stands was '*S3301*' with 25 plants m^{-2}. The lowest stands were produced by variety '*S3276*' (8 plants m^{-2}) and was not different from varieties '*ES107*', '*ES108*', '*S3251*', '*ES103*', and '*S39*'; stand counts ranged from 8 to 14 plants m^{-2} ($P = 0.0087$). We found no differences in stand count among sesame varieties in any of the locations in 2022 ($P > 0.05$). There was no clear trend found regarding a variety consistently producing higher

stand counts 2 to 3 WAP. The only variety that stood out was '*S3301*' in Jackson Springs 2021, where it produced significantly higher stands than any other variety in that location. Variety '*S3251*' produced the highest stands in Piedmont 2021 and was among the highest stand producing varieties in Clinton for that same year. In 2022, the average stand count 2 to 3 WAP across locations was 41 plants m^{-2}.

Fifteen weeks after planting

We found differences in stand count among sesame varieties in Jackson Springs 2021 (Table 2.5). Variety '*S3301*' (28 plants m^{-2}) had the highest density and was not different from varieties '*ES107*', '*S39*' and '*ES103*'; stand counts ranged from 14 to 28 plants m^{-2} ($P = 0.0340$). The variety with the lowest stands was '*ES108*' (7 plants m^{-2}) and was not different from varieties '*S39*', '*ES103*', '*S3251*' and '*S3276*'; stand counts ranged from 7 to 20 plants m^{-2}. Stands in this location were exceptionally low compared to all other locations in both years; the average stand 15 WAP across varieties was 17 plants m^{-2}. This location received 1.4 cm of rain after planting that washed the seed deep into the furrow, preventing it from emerging and influenced stand establishment. Herbicide application at planting also affected the stand. We found no difference in stand count among varieties for Clinton and Piedmont in 2021; average stand count in these locations were 73 and 41 plants m^{-2}, respectively. The population counted for Clinton was higher than the expected population based on what we planted. Two scenarios could have caused this to occur. We had to re-plant this location into the same field after tillage due to no emergence on the first attempt. Sesame's germination period may extend up to three weeks depending on temperature, soil type and moisture availability (Langham, 2007). We may have had some plants from the previous planting emerge when we collected the data. The second scenario could have been a middle-loading of the plots. If the cone for the planter is not level

enough, the seed will not distribute around the cone evenly which may result in middle-loading of plots with more seed than on the ends. Then, even if the planted population is accurate per plot, the plants may be concentrated in the centers of the plots, causing higher than expected stand counts. Ahmad et al. (2002) obtained similar results in a one-year row spacing and variety trial in Pakistan, the authors found no differences in stand between two varieties. Similarly, in Florida, Gloaguen et al. (2018) found no difference in stand density between two varieties planted in May and July, but did find differences in the interaction between planting date and varieties when planted in June. The same authors conducted a three-year row spacing trial using two varieties in 2012-2013, and four varieties in 2013-2014. They found no difference in plant density among any of the varieties used in those years. In both Clinton and Piedmont 2021, we observed an increase in stand at harvest compared to stand at emergence. Sesame's germination time is usually from three to five days when planted into good moisture (Langham, 2007). If temperatures fall below 21 °C, germination can be delayed, or if temperatures rise above 25 °C, it can be encouraged (Namiki, 1995; Weiss, 1971). Adequate soil moisture is important to achieve successful stand establishment, but rain will often move the seed deeper or create a crust in certain types of soils (Langham, 2007; Sheahan, 2014). Piedmont received 1.12 cm of rain the day after planting, which leads us to believe it caused a delay in germination due to crust on the clay soil, thus the increase in stand 15 WAP. The sandy soils in Clinton and the 1.27 cm of irrigation the plants received at planting, might have been part of why germination took longer and stands were higher 15 WAP. We did not find differences in stand in any of the locations in 2022; average stand count was 35 plants m^{-2}. We found no differences in 2022; we observed a reduction in stand 15 WAP in Piedmont and some varieties in Plymouth. There is a strong competition between seedlings within a row, causing weaker plants to produce few

capsules or die (Langham, 2008). This self-thinning leads to a decrease in plant stand at harvest compared with plant stand at emergence, though we still observed high yields in both of these locations (Langham 2007; Grichar et al., 2012).

Average plant height

Sesame variety had no effect on plant height in any of the locations in 2021 (Table 2.6). Average plant height ranged from 103 to 114 cm in Piedmont, 21 to 30 cm in Clinton and 96 to 116 cm in Jackson Springs. These results are in line with Gloaguen et al. (2018), where they found no difference in plant height between two varieties planted at 19.0 and 38.1 cm in Citra, Fl. in 2012 and 2013. Similarly, the authors did not find differences in plant height among four varieties tested in 2013 and 2014. Naim et al. (2012), conducted a seeding rate and variety trial in Sudan, and observed no difference in plant height among varieties in one of their locations. We found differences in plant heights for Piedmont 2022 ($P = 0.0025$). Variety '*S3301*' produced the tallest plants (137 cm) but was not different from varieties '*4302*' (135 cm) and '*S39*' (134 cm). The shortest plants were '*ES108*' (121 cm) which was not different from varieties '*S3276*', '*ES103*', '*S3251*' and '*ES201*'; average heights ranged from 121 to 127 cm. We found differences on average plant height among varieties for Plymouth 2022 ($P = 0.0001$; Table 2.6). The tallest plants were variety '*4302*' (164 cm) and not different from variety '*S3276*' (157 cm). Variety '*ES201*' (131 cm) had the shortest plants and did not differ from varieties '*S3251*' (135 cm), '*ES108*' (138 cm) and '*S3301*' (142 cm). These results are in line with that of Kashani et al. (2015), who reported variety '*S-17*' produced taller plants than variety '*Pr-125*', when testing five nitrogen and phosphorous rates in a one-year study in Pakistan. Valiki et al. (2015) found similar results in a one-year plant density study, testing three sesame varieties in Iran. The authors found plant height differed among varieties, with plants ranging from 127.6 to 190.5 cm.

Similar results were obtained by Ahmad et al. (2002), where variety '*TS3*' produced taller plants than variety '*92001*', in a one-year row spacing study in Pakistan. Hoque et al. (2007), found differences in plant height among three sesame varieties in a one-year sulfur rate trial in Bangladesh. Ali et al. (2020) conducted a similar study looking at different plant spacing and variety performance in Sudan. They found that three varieties produced statistically different plant height at different spacing in both years. Similarly, Naim et al. (2012) found no difference between two varieties but both were different from their third variety. There were no differences in average plant height among sesame varieties in Jackson Springs 2022 (Table 2.6). Average plant height for this location ranged from 116 to 123 cm. Average heights across varieties ranged from 96 to 164 cm throughout all locations for both years with Clinton as the exception, where heights averaged 26 cm. These heights fall into the international plant height range which is from 56 to 311 cm tall (Langham, 2019). Sesame is a plastic crop, and yields may not be affected by plant height (Grichar et al., 2011); however, Clinton had the lowest yields due to herbicide damage and heavy rainfall (Table 2.3).

Average capsule count

Average capsule count was not different among varieties in Clinton and Piedmont for 2021 (Table 2.7). Average capsule count across varieties was 24 for Clinton and 95 for Piedmont. These results are in line with those from Gloaguen et al. (2018) where they found no difference in number of nodes on the main stem among varieties in Citra, Fl when planted at different row spacing in 2012 and 2013. Naim et al. (2012) compared three varieties under different row spacing in Sudan and found two varieties produced similar capsule counts. We found differences in capsule count among varieties in Jackson Springs 2021 ($P = 0.0066$). Variety '*S3276*' (196) yielded the highest amount of capsules and was not different from variety

‘*ES108*’ (189). The variety that yielded the least amount of capsules was ‘*S3301*’ (60) and was not different from varieties ‘*S39*’, ‘*ES103*’, ‘*S3251*’ and ‘*ES107*’; average capsule ranged from 60 to 106. There were differences in average capsule count among varieties in Piedmont 2022 (*P* = 0.0495; Table 2.7). The highest amount of capsules was produced by variety ‘*S3301*’ (132) and was not different from variety ‘*ES103*’ (130). The variety with the lowest capsule count was ‘*S3276*’ (78) and was not different from varieties ‘*S39*’, ‘*4302*’, ‘*ES201*’, ‘*ES108*’ and ‘*S3251*’; average capsule count ranged from 78 to 107 capsules per plant. We found differences in capsule count in Jackson Springs 2022 (*P* = 0.0232; Table 2.7). Variety ‘*S39*’ (102) produced the highest capsule count but was not different from varieties ‘*4302*’, ‘*ES103*’, and ‘*S3276*’; average capsule count ranged from 85 to 102. The variety with the least amount of capsules was ‘*S3251*’ (63) and was not different from varieties ‘*S3276*’, ‘*ES201*’, ‘*ES108*’ and ‘*S3301*’; average capsule count ranged from 63 to 85. Hoque et al. (2007) found differences in capsule count among sesame varieties tested in Bangladesh in a one-year sulfur level study. Gloaguen et al. (2018) conducted similar studies, where they found that node count varied across varieties when planted at different spacing. Ahmad et al. (2002) tested two varieties under different plant spacing and found one variety produced more capsuled than the other did. Kashani et al. (2015) found differences in capsule count between varieties in Pakistan when testing different nitrogen and phosphorous doses. Capsule count is genetically regulated by a single gene but can be highly influenced by the environment (Langham, 2007). The high germplasm variability present in sesame may attribute the differences observed in capsule count at Piedmont and Jackson Springs. The same variety can develop differently in different environments, depending on moisture availability and fertility (Zhang et al., 2021).

Yield

We did not observe differences in yield among varieties in Clinton or Jackson Springs 2021 (Table 2.8). Yields in Clinton averaged 247.94 kg ha^{-1}, which were exceptionally low due to the environmental conditions present in this field. Excessive precipitation and herbicide carryover affected the crops performance throughout the growing season (Table 2.3). In Jackson Springs, the average yield was 542.39 kg ha^{-1} and we attribute this to the poor plant stand. This location received 1.4 cm of rain within 5 days of planting, which washed the seed deep into the furrow, preventing it from emerging. Additionally, herbicide application at planting had a detrimental effect in germination, consequently affecting yield. The lack of differences in these locations is not due to variety but to poor field quality and management. Gloaguen et al. (2018) found that there were no differences in yield between two varieties at different planting dates. The same authors conducted a row spacing trial and found no differences in yield between two varieties when planted at 19 or 38.1 cm spacing; they observed differences in yield at different row spacing. Naim et al. (2012) found no differences in seed yield among three sesame varieties used in a seed rate study in Sudan. We found differences in yield among varieties in Piedmont 2021 ($P < 0.0001$). The highest yielding variety was '*S39*' with 2,307.52 kg ha^{-1} and was not different from varieties '*S3301*', '*S3251*' and '*S3276*'; yields ranged from 1,716.98 to 2,307.52 kg ha^{-1}. Variety '*ES108*' (694.52 kg ha^{-1}) yielded the lowest and was not different from varieties '*ES103*' (752.87 kg ha^{-1}) and '*ES107*' (1,255.25 kg ha^{-1}). We observed differences in yield among varieties in Piedmont 2022 ($P = 0.0318$). Variety '*S3301*' yielded the highest with 2,709.81 kg ha^{-1}, but was not different from varieties '*S39*', '*S3251*', '*4302*', '*S3276*' and '*ES103*'; yields ranged from 2,277.82 to 2,709.81 kg ha^{-1}. Variety '*ES201*' (1,937.37 kg ha^{-1}) yielded the lowest and was not different from varieties '*S3251*', '*S3276*', '*ES108*' and '*ES103*'. Sesame yields

were significantly different by variety in Jackson Springs 2022 (P = 0.0015). Variety '*S39*' (1,680.64 kg ha^{-1}) produced the highest yield and was not different from varieties '*S3251*', '*4302*', '*S3276*' and '*ES201*'; yields ranged from 1,348.10 to 1,680.64 kg ha^{-1}. The lowest yielding variety was '*S3301*' (863.87 kg ha^{-1}) and was not different to variety '*ES108*' (1,105.83 kg ha $^{-1}$). In Plymouth 2022, we found differences in yield among sesame varieties (P = 0.0455; Table 2.6). The highest yielding variety was '*S39*' (1,647.04 kg ha^{-1}) and was not different from varieties '*S3251*', '*4302*', '*S3276*' and '*ES103*'; yield ranged from 1,233.99 to 1,647.04 kg ha^{-1}. Variety '*ES201*' (944.93 kg ha^{-1}) produced the lowest yields and was not different from varieties '*S3301*', '*4302*', '*S3276*' and '*ES108*'; yields ranged from 966.50 to 1,275.36 kg ha $^{-1}$. These results are in line with Gloaguen et al. (2018), which found significant differences in yield among varieties when planted at 19, 38.1 and 76.2 cm spacing in Live Oak, FL in 2013. Conversely, the same authors found no difference in yield among varieties in 2014. Ali et al. (2020) found differences in yield among three sesame varieties planted at four different plant spacing. Similarly, Kashani et al. (2015), found differences in yield between two varieties used in a fertilizer rate trial. Hoque et al. (2007), found differences in yield when comparing three sesame varieties in a one-year sulphur level study in Bangladesh. In 2022, we timed our planting so it would not coincide with rain events that are detrimental to germination in certain soil types. When variety was significant, '*S39*' was the highest or among the highest yielding varieties. This variety was not different from varieties '*S3251*' and '*S3276*' in both years and to variety '*4302*' in 2022. Variety '*ES108*' was often among the lowest yielding varieties however, average yield in 2022 for this variety was 1,365.71 kg ha^{-1}, which is considerably high. This variety was a poor performer of very high yielding varieties. We observed that in environments where yields were lower, yields from this variety were even lower. Sesame germplasm has a lot of variability; the

same genotype can develop differently under different conditions and different genotypes may develop differently in the same condition (Langham, 2007).

Correlations

We ran Pearson correlations to look for relationships between height, stand count at harvest, capsule count and yield (Table 2.9). Throughout locations, plant height was positively correlated with yield, capsule count or both. In Clinton 2021, we observed a strong correlation between plant height, capsule count and yield. Taller plants produced more capsules and higher yields. Stand count had no effect on any of the other variables analyzed. Similarly, in Jackson Springs 2021, plant height had a strong correlation with yield and capsule count. In this location, we observed a negative correlation between stand count and capsules; at higher plant density, less capsules were produced. Direct sunlight has an effect on the amount of branches each plant will produce. When there is sunshine at the second pair of leaf axils of a branch, there can be a branch formation, however, at lower light, a capsule will form (Langham, 2007). In high populations and as the plants grow, leaves begin to shade the axillary flowers, preventing them from forming capsules. There is very strong correlation between the lack of sunlight and a low number of axillary capsules; it is unknown at what point the light affects the capsule development (Langham, 2007). Additionally, there is a strong correlation between branches per plant and capsules (Delgado & Yermanos, 1975; Khidir & Osman, 1970). This leads us to hypothesize that less capsules were seen at higher densities because of the lack of sunshine, which caused less branch formation and led to fewer capsules. Height was strongly correlated with capsule count in Jackson Springs 2022. Harvest stand had a positive correlation with yield in Piedmont 2021. At higher densities, sesame tends to grow faster and shade competing weeds

(Langham, 2008). This might have allowed the crop to utilize the available moisture and fertility, which translated in higher yields.

CONCLUSION

The objectives of this variety trial conducted in 2021 and 2022 were to identify which sesame varieties would perform better in North Carolina to optimize yield and develop recommendations. Yields obtained in this study are comparable to those expected in the southwest. Variety '*S39*' had the highest yielding potential for Piedmont, Jackson Springs and Plymouth environments. Although other varieties such as '*S3251*', '*4302*', '*S3276*' and '*ES108*', '*ES201*' produced lower yields, their production potential was still high. We observed that higher yields were not always related with the variety's agronomic traits such as height and capsule count. Altogether, this study has demonstrated that sesame production in North Carolina is feasible when using the appropriate variety. However, more research in this crop is needed to evaluate appropriate planting date and weed management for this region.

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Table 2.1 Chemistries used for weed control in sesame fields in 2021 and 2022.

Location	Time of application	Product name	Active Ingredient	Rate (g ai ha^{-1})
Clinton 2021	Preemergence	Roundup Original Max	Glyphosate	850.92[X]
	Postemergence	Dual Magnum	S-metolachlor	1,977.10
	Postemergence	Diuron 4L	Diuron	576.12
Sandhills 2021	Preemergence	Buccaneer Plus	Glyphosate	855.73
	At planting	Dual II Magnum	S-metolachlor	1,321.52
Sandhills 2022	Preemergence	Treflan	Trifluralin	691.90
	Postemergence	Dual II Magnum	S-metolachlor	1,321.52
Salisbury 2021	Postemergence	Diuron 4L	Diuron	576.12
	Postemergence	Roundup PowerMAX 3	Glyphosate	1,382.15
Salisbury 2022	Preemergence	Treflan 4L	Trifluralin	691.90
	Preemergence	Gramoxone SL 3.0	Paraquat	542.10
Tidewater 2022	Preemergence	Treflan 4L	Trifluralin	691.90
	Postemergence	Clethodim 2E	Clethodim	288.06

The chemistries used were subject to availability in each Research Station.
[X] Glyphosate reported in grams of acid equivalent per hectare.

Table 2.2 Sesame variety overview.

		Agronomic trait			
Company	Variety	Maturity*	Branch*	Capsule*	Height*
Equinom	ES103	Late	Ultra branched	Triple	Tall
Equinom	ES107	Medium	Single stem	Triple	Medium
Equinom	ES108	Medium	Basal Branched	Triple	Medium
Equinom	ES201	Medium	Basal Branched	Triple	Tall
Sesaco	S39	Medium-Late	Branched	Single	Medium-Tall
Sesaco	S3301	Medium-Late	Branched	Single	Medium
Sesaco	S3251	Medium	Branched	Single	Medium
Sesaco	S3276	Medium	Branched	Single/Triple	Medium
Sesaco	4302	Medium-Late	Branched		

*Agronomic trait information was extracted from each company's variety information available for the growers.

Table 2.3 Average temperature and total rainfall by month during the sesame growing seasons in 2021 and 2022 at each research station.

Location	May		June		July		August		September		October		November		Total
	°C	Rainfall (cm)	°C	Rainfall (cm)	°C	Rainfall (cm)	°C	Rainfall (cm)	°C	Rainfall (cm)	°C	Rainfall (cm)	°C	Rainfall (cm)	Rainfall (cm)
Clinton															
2021	-[Y]	-	24.5	14.5	25.7	31.7	26.1	17.3	22.9	5.5	19.3	6.1	-	-	75.1
30 yr	-	-	24.8	12.4	26.8	14.3	25.8	14.2	22.7	16.0	16.9	8.6	-	-	65.5
Jackson Springs															
2021	-	-	23.6	15.1	25.0	12.1	25.2	13.5	22.2	10.7	18.9	10.3	-	-	61.7
2022	-	-	24.9	7.7	26.1	10.0	24.8	9.0	21.5	13.3	15.6	1.4	-	-	41.3
30 yr	-	-	24.4	11.3	26.4	11.9	25.7	10.7	22.2	12.0	16.3	9.0	-	-	54.9
Piedmont															
2021	-	-	23.3	12.2	25.0	9.4	25.0	7.8	21.0	8.7	17.9	2.2	8.8	2.7	43.0
2022	-	-	24.4	0.8	25.7	20.7	24.1	9.4	19.8	16.1	13.3	3.1			50.0
30 yr	-	-	23.7	10.8	25.6	11.0	24.8	10.3	21.4	10.2	15.3	8.0	9.6	8.4	58.7
Plymouth															
2022	21.2	0.8	24.1	6.4	26.2	14.2	24.8	16.3	21.5	21.1	-	-	-	-	58.7
30 yr	20.2	9.8	24.4	12.6	26.4	14.8	25.6	15.8	22.8	14.9	-	-	-	-	67.9

[X] 30 year average calculated from 1990 to 2020 and collected from NOAA NCEI

[Y] Data not included for months outside the planting and harvest dates.

Weather data retrieved from the State Climate Office of North Carolina with the Cardinal Request Builder tool.

Table 2.4 Effect of sesame varieties on stand count two to three weeks after planting in 2021 and 2022.

	Location					
	Clinton	Piedmont		Jackson Springs		Plymouth
Variety	2021	2021	2022	2021	2022	2022
	Stand count (plants m^{-2})[Z]					
ES107	68 a [X]	18 b	-	14 b	-	-
ES108	67 a	40 a	43	9 b	30	44
S3251	60 a	41 a	49	11 b	32	47
S3301	53 ab	24 bc	46	25 a	28	49
ES103	59 ab	34 ac	42	12 b	33	41
S39	54 ab	37 ac	44	13 b	30	47
S3276	43 b	35 ac	34	8 b	28	49
4302	-[Y]	-	53	-	44	58
ES201	-	-	30	-	31	41
p-value	0.0348	0.0186	0.3180	0.0087	0.7382	0.9479

[X] Means within a location and year that share a common letter are not significantly different (α=0.05)

[Y] Varieties '*4302*' and '*ES201*' were not included in 2021; variety '*ES107*' was not included in 2022.

[Z] Stand counts were calculated by dividing the data collected in the field by 0.381 to get plants m^{-2}.

Table 2.5 Effect of sesame varieties on stand count fifteen weeks after planting in 2021 and 2022.

	Location					
	Clinton	Piedmont		Jackson Springs		Plymouth
Variety	2021	2021	2022	2021	2022	2022
	Stand count (plants m^{-2})[Z]					
S3301	69	47	33	28 a [X]	50	32
ES107	70	31	-	26 ab	-	-
S39	81	46	27	20 abc	40	23
ES103	73	30	27	14 abc	48	35
S3251	79	58	37	13 bc	47	40
S3276	64	50	25	9 c	45	28
ES108	78	23	33	7 c	37	43
4302	-[Y]	-	34	-	38	30
ES201	-	-	28	-	31	33
p-value	0.8929	0.0907	0.6587	0.0340	0.5702	0.2393

[X] Means within a location and year that share a common letter are not significantly different (α=0.05)

[Y] Varieties '*4302*' and '*ES201*' were not included in 2021; variety '*ES107*' was not included in 2022.

[Z] Stand counts were calculated by dividing the data collected in the field by 0.381 to get plants m^{-2}.

Table 2.6 Effect of sesame varieties on average plant height fifteen weeks after planting in 2021 and 2022.

	Location					
	Clinton	Piedmont		Jackson Springs		Plymouth
Variety	2021	2021	2022	2021	2022	2022
			Height (cm) [Z]			
4302	-	-	135 a [X]	-	123	164 a
S3276	30	106	127 bc	116	123	157 ab
S39	27	113	134 ab	106	121	151 bc
S3301	29	108	137 a	99	116	142 cde
ES103	24	104	125 bc	96	116	147 bcd
3251	29	106	125 bc	110	119	135 de
ES108	23	114	121 c	107	116	138 de
ES201	-[Y]	-	121 c	-	116	131 e
ES107	21	108	-	103	-	-
p-value	0.1489	0.7062	0.0025	0.4497	0.5157	0.0001

[X] Means within a location and year that share a common letter are not significantly different (α=0.05)

[Y] Varieties '*4302*' and '*ES201*' were not included in 2021; variety '*ES107*' was not included in 2022.

[Z] Plants were measured from the soil to the base of the apical meristem.

Table 2.7 Effect of sesame varieties on average capsule count fifteen weeks after planting in 2021 and 2022.

	Location				
	Clinton	Piedmont		Jackson Springs	
Variety	2021	2021	2022	2021	2022
	Average capsule count (capsules/plant)[Z]				
ES107	18	106	-	99 b	-
S39	18	84	82 b [X]	106 b	102 a
4302	-[Y]	-	84 b	-	91 ab
ES103	28	126	130 a	89 b	89 abd
S3276	34	102	78 b	196 a	85 abcd
ES201	-	-	107 b	-	66 cd
ES108	20	96	105 b	189 a	75 bcd
S3251	24	73	83 b	102 b	63 c
S3301	28	81	132 a	60 b	65 c
p-value	0.1074	0.1951	0.0495	0.0066	0.0232

[X] Means within a location and year that share a common letter are not significantly different (α=0.05)

[Y] Varieties '*4302*' and '*ES201*' were not included in 2021; variety '*ES107*' was not included in 2022.

[Z] Capsules were counted from five representative plants per treatment plot.

Table 2.8 Effect of sesame varieties on yield in 2021 and 2022.

	Location					
	Clinton	Piedmont		Jackson Springs		Plymouth
Variety	2021	2021	2022	2021	2022	2022
			Yield (kg ha^{-1})			
S39	241.27	2,308.48 a [X]	2,607.78 a	547.24	1,680.64 a	1,647.04 a
S3301	286.75	1,943.38 a	2,709.81 a	583.41	863.87 b	966.50 bc
S3251	229.93	2,2671.58 a	2,463.10 ab	538.54	1,507.43 ac	1,418.71 ab
4302	- [Y]	-	2,684.44 a	-	1,559.56 ac	1,275.36 abc
S3276	265.18	1,716.98 ab	2,284.57 ab	578.88	1,348.10 acd	1,233.99 abc
ES103	252.80	752.87 c	2,277.82 ab	415.43	1,336.59 cd	1,410.78 ab
ES108	244.86	694.52 c	1,940.00 b	651.81	1,105.83 bd	1,051.30 bc
ES201	-	-	1,937.37 b	-	1,395.23 acd	944.93 c
ES107	207.77	1,255.25 bc	-	482.40	-	-
p-value	0.9212	<0.0001	0.0318	0.9196	0.0015	0.0455

[X] Means within a location and year that share a common letter are not significantly different (α=0.05)
[Y] Varieties '*4302*' and '*ES201*' were not included in 2021; variety '*ES107*' was not included in 2022.

Table 2.9 Correlations between average height and yield and capsule count for sesame in 2021 and 2022.

Location	Average height (cm)	Yield (kg ha^{-1})	Capsules	Harvest stand
Clinton 2021				
Average height (cm)	1			
p-value				
Yield (kg ha-1)	0.64806	1		
p-value	*0.0003*			
Capsules	0.83174	0.61103	1	
p-value	*<0.0001*	*0.0009*		
Harvest stand	0.21374	0.19375	-0.04886	1
p-value	*0.2944*	*0.3429*	*0.8127*	
Jackson Springs				
2021				
Average height (cm)	1			
p-value				
Yield (kg ha-1)	0.61755	1		
p-value	*0.0006*			
Capsules	0.44054	0.27247	1	
p-value	*0.0215*	*0.1691*		
Harvest stand	0.04917	0.15541	-0.50817	1
p-value	*0.8076*	*0.4389*	*0.0068*	
2022				
Average height (cm)	1			
p-value				
Yield (kg ha-1)	0.22725	1		
p-value	*0.2110*			
Capsules	0.50015	0.21972	1	
p-value	*0.0036*	*0.2269*		
Harvest stand	-0.25481	-0.03705	-0.13347	1
p-value	*0.1593*	*0.8405*	*0.4665*	
Piedmont				
2021				
Average height (cm)	1.00000			
p-value				
Yield (kg ha-1)	0.21194	1		
p-value	*0.2789*			
Capsules	0.35187	-0.31454	1	
p-value	*0.0663*	*0.1031*		
Harvest stand	0.22861	0.65207	-0.03921	1
p-value	*0.2420*	*0.0002*	*0.8430*	

Table 2.9 (continued)

Location	Average height (cm)	Yield (kg ha^{-1})	Capsules	Harvest stand
2022				
Average height (cm)	1			
p-value				
Yield (kg ha-1)	0.74189	1		
p-value	*<0.0001*			
Capsules	-0.12275	-0.22114	1	
p-value	*0.5181*	*0.2402*		
Harvest stand	0.04759	0.15708	-0.09012	1
p-value	*0.8028*	*0.4071*	*0.6358*	
Plymouth 2022				
Average height (cm)	1			
p-value				
Yield (kg ha-1)	0.5737	1		
p-value	*0.0006*			
Capsules	-[X]	-	1	
p-value	-	-		
Harvest stand	-0.10853	-0.10048	-	1
p-value	*0.5543*	*0.5843*	-	

[X] Capsule count was not collected in Plymouth 2022.

CHAPTER THREE

Evaluation of the effect of nitrogen rate on Sesame (*Sesamum indicum* L.)

ABSTRACT

Production levels of sesame (*Sesamum indicum* L.) in the United States are below total domestic consumption. Historically, sesame has been grown in the Southwestern parts of the country. The Southeast may be suitable for expanded sesame production. Research regarding agronomic recommendations such as the effect of applied fertility on plant growth and yield are limited for this region. Field trials were conducted across North Carolina's small grain production regions to assess optimal nitrogen (N) rates. Studies were conducted in the Coastal Plains, Piedmont, Tidewater, and Sandhills in 2021 and 2022. Sesame variety '*ES103*' was planted in experimental plots at a constant population of 559,723 seeds ha^{-1} to test the effect five nitrogen rates (0, 56, 112, 167 and 224 kg N ha^{-1}) on plant growth parameters. Data collected included at harvest stand count, plant height, capsule count, leaf N concentration and seed yield. Nitrogen rate did not affect stand count in any of the environments but did produced varying effects to plant height, capsule count and yield. In 2021, we saw no effect in average plant height and capsule count, except for Clinton. The only location that observed changes in height, capsule count and yield as N rate increase was Sandhills in 2022. We observed no changes in the metrics in Tidewater 2022 and in Salisbury 2021. Leaf N concertation observed a positive increase as N rate increased in all locations. However, the increase in leaf N concentration did not always result in increases in seed yield. Our results indicate that N may have an effect on some plant growth parameters but will depend on location, and environmental condition.

INTRODUCTION

Sesame (*Sesamum indicum* L.) is one of the oldest cultivated crops, dating back to 5,500 BC (Bedigian & Harlan, 1986). It is an erect, indeterminate, annual plant that belongs to the family of *Pedaliaceae* (Couch et al., 2017a; Namiki, 1995). Its origin can be traced back to East Africa or Asia, spreading into the Mediterranean and the Far East (Ashri, 1998; Langham et al., 2002). Sesame seed can be used whole or decorticated in pastries or sweets (Couch et al., 2017a). In many countries in the Middle East, sesame seed is ground into a paste called tahini, which is often mixed with ground chickpeas to prepare hummus (Couch et al., 2017a; Langham et al., 2002). Sesame oil is considered, gastronomically and chemically, as a superior quality oil (Levey, 1959). It is often referred to as the "queen of oilseeds" because it contains lignans sesamin and sesamolin that prevent oxidative rancidity, extending shelf life and making it a desirable cooking oil (Bedigian & Harlan, 1986; Nayar & Mehra, 1970). Adding sesame oil can extend the shelf life of other oil-containing products, such as peanut butter (Ashri, 2007). In Japan, Korea and China, sesame oil is a popular cooking oil and it is also consumed for its medicinal qualities (Langham et al., 2002). The lignans present in the oil are beneficial fibers that have cholesterol-lowering effects in humans that help prevent high blood pressure. Sesame seed is high in protein, vitamin B1 and is an excellent source of phosphorus, zinc, copper, iron, calcium and magnesium (Pathak et al., 2014). In the United States (US), it is used on top of crackers and breads and its use as an ingredient has increased over the past years (Langham, 2008).

Sudan, India and the United Republic of Tanzania are among the leading producers of sesame, contributing 16.4, 11.9, and 10.3% of the global production, respectively (FAO, 2020). It is a relatively new crop in the US and production in the last decade has been limited to Texas,

Oklahoma, Arizona and Kansas (Dossa et al., 2017; Gloaguen et al., 2018; Grichar et al., 2011; Langham, 2007). However, current production levels do not meet the growing domestic consumption, which leaves the country dependent on imported sesame seed (Gloaguen et al., 2018; Smith et al., 2000). In 2021, imports reached 37,000 tons, with a net worth of $82.3 million (FAO STAT, 2023). This opens an opportunity for a profitable domestic market if US production can expand to meet demand. Although breeders have bred this crop for production in the Southwestern US, declining water resources in this region pose a threat to crop production (Grichar et al., 2011; Macdonald, 2010; Mpanga & Idowu, 2021). This generated a need and interest to explore other suitable areas for sesame production. The Southeast may be a suitable region due to its warm, long growing season, and greater annual precipitation compared to the Southwest (Couch et al., 2017a; Gloaguen et al., 2018).

Sesame is a survivor crop. Farmers have planted it in areas that will not support the growth of other crops and under drought and/or extreme heat conditions. It can contribute agroecosystem services such as nematode suppression, improved soil quality by preventing nutrient leaching, reduce irrigation needs, and increase wildlife and pollinator habitat (Ashri, 1998; Bedigian & Harlan, 1986; Couch et al. 2017a; Kamel et al., 2013; Oplinger et al., 1990). Some counties grow it during the monsoon season or at the very edge of the desert (Langham, 2007; Langham, 2008). It has the potential to increase agricultural water-use efficiency in the southeastern cropping system because it is considered one of the most drought-tolerant crops in the world, thus reducing the need to irrigate (Langham et al., 2008). This characteristic is attributed to its strong taproot and its branched feeder root system that allows it to penetrate deep into the soil to find moisture (Langham, 2008; Oplinger et al., 1990). Sesame roots penetrate the soil deeper than most crops, thus reaching a reservoir of fertility otherwise lost (Couch et al.,

2017a; Langham, 2008). This means sesame would serve as a very effective catch crop in highly leachable soils (Couch et al., 2017a).

Limited amounts of sesame are grown under high input conditions, but as with every crop, yields improve dramatically under increased input (Langham, 2007). Agronomic inputs such as irrigation and nitrogen are important for boosting seed yield and yield components in sesame (Damdar et al., 2014). Nitrogen is the most dynamic and limiting nutrient for crop production in many regions of the world (Frageria & Baligar, 2005; Wu et al., 2009). It contributes up to 50% of all nutrient inputs and is the most important essential nutrient for plant nutrition (Babajide & Oyeleke, 2014; Frageria & Baligar, 2005). Its critical role in plant growth and development, as well as its involvement in cell differentiation and elongation and protein metabolism, makes it difficult to substitute in crop production (Ahmad et al., 2001; Babajide & Oyeleke, 2014; Frageria & Baligar, 2005). Increasing nitrogen supply results in leaf area development, increase in carboxylases and chlorophyll content and productive sink, all which increase photosynthetic capacity (Ahmad et al., 2001; Ali et al., 2010). Additionally, it enhances root development, which improves nutrient and water uptake, resulting in greater resource allocation (Ali et al., 2010; Babajide & Oyeleke, 2014). Unfortunately, soil nitrogen not taken up by the plants is easily lost to the environment due to leaching, volatilization, surface runoff and denitrification (Austin et al., 2013; Rosolem et al., 2017). Considering that fertilizer accounts for 26% of a growers operating cost and that fertilizer prices have increased over the last years, it is important to optimize nitrogen use and application (USDA, 2021).

Nitrogen fertilization has a profound effect on oilseed crops (Malik et al., 2003). Many authors have reported the positive effects nitrogen application has on sesame's plant height, capsule count, density and yield. Bellaloui et al. (2018) observed an increase in yield as nitrogen

rate increased. Malik et al. (2003) observed taller plants, more capsules per plant and higher yields with 80 kg N ha^{-1} in Pakistan. Similarly, El Mahdi (2008) concluded that taller plants where produced when nitrogen and phosphorus levels were 88 and 44 kg ha^{-1}, respectively. Conversely, the same author found no difference in plant density. Noorka et al. (2011) observed taller plants, more capsules per plant and higher yields when applying 205 kg N ha^{-1}. Damdar et al. (2014) found that 90 kg N ha^{-1} produced more capsules per plant and higher seed yield. Shehu et al. (2010) found no difference in plant height among the nitrogen rates, but observed higher capsule count and yield with 75 and 112 kg N ha^{-1}. However, there is limited data on nitrogen rate recommendations for sesame grown in the Southeast US. The objectives of this study were to identify the appropriate nitrogen rate in diverse soils throughout North Carolina to optimize sesame yields and develop recommendations for growers seeking to produce this crop.

MATERIALS AND METHODS

We conducted field experiments in 2021 and 2022 at three locations around North Carolina. In 2021, fields were located at the Sandhills Research Station in Jackson Springs (35°11'06.6"N 79°40'52.5"W) on Candor sand (Sandy, kaolinitic, thermic Grossarenic Kandiudults), Piedmont Research Station in Salisbury (lat. 35°41'56.8"N, long. 80°37'08.0"W) on Lloyd clay loam (fine, kaolinitic, thermic Rhodic Kanhapludults), and the Horticultural Crops Research Station in Clinton (lat. 35°01'20.4"N, long. 78°16'36.1"W) on Orangeburg loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudults). In 2022, we conducted the experiments at the Tidewater Research Station in Plymouth (lat. 35°52'17.8"N, long. 76°39'39.4"W) on Cape Fear loam (Fine, mixed, semiactive, thermic Typic Umbraquults), Salisbury and Sandhills.

We tilled the fields and sprayed for weed control before planting (Table 3.1). Variety '*ES103*' (Equinom Ltd., Givar Brenner, Israel) was planted using a small plot drill (Plot Motion

xl, Wintersteiger, Ried im Innkreis, Austria) at a constant population of 559,723 seeds ha^{-1}. In both years, we accomplished weed control through chemical applications and hand cultivation as necessary (Table 3.1). We irrigated the fields one day before, the day of, or after planting to promote seed germination based on field conditions. The only location with no irrigation system available was Tidewater. We evaluated five nitrogen treatments: 0, 56, 112, 167 and 224 kg N ha^{-1}. The nitrogen source was granular urea (46-0-0 SUPERU®; Koch Agronomic Services, Wichita, KS) and split-applied by hand. The first application was made 2 weeks after planting (WAP) and the second application was made 6 WAP. We arranged the treatments in a randomized complete block design with four blocks in all locations for both years. Plot dimensions were 1.5 m wide by 6.1 m long.

Data Collection

Stand counts were collected 15 weeks after planting (WAP) in both years. We counted two meters of row representative of the plot to evaluate the stand. We collected plant height and whole plant capsule count from five representative plants per plot 15 WAP. We measured plant height from the soil to the base of the apical meristem. Leaf samples were collected 4, 6, 8, and 10 WAP by cutting the most recently expanded leaf from 15 randomly selected plants from each treatment plot. We dried the leaves at 65 °C for 48 h, ground, and submitted for analysis of nitrogen content at the North Carolina Department of Agriculture & Consumer Services (NCDA&CS) Agronomic Division Plant lab (Raleigh, NC).

The trials were harvested 15-21 WAP in 2021 and 16-21 WAP in 2022 with a small plot combine (Quantum Pro, Wintersteiger, Ried im Innkreis, Austria). We used glyphosate (Roundup Pro®, Bayer, Leverkusen, Germany) at 855.73 grams of acid equivalent per ha^{-1} or

saflufenacil (Sharpen®, BASF The Chemical Company, Ludwigshafen, Germany) at 38.55 grams of active ingredient per ha^{-1} as harvest aids 3 to 7 days prior to harvest.

Yield was calculated from each treatment plot using the total weight and moisture given by a grain gauge (HarvestMaster, Juniper Systems, Logan, UT) on the combine. When plot weights were low and the grain gauge did not provide moisture, it was measured using a grain moisture tester (DICKEY-john® Corporation GAC®2000 Grain Analysis Computer, Auburn, IL) upon returning from the field. We collected harvest samples from the combine and took them back to the lab to measure moisture content. We placed the samples on metal trays to air dry for 72 h or until moisture content was below 10%. When moisture content was below 10%, we cleaned each sample using a 4.76 mm round (scalper) precision and a 1.98 mm triangle precision sieves (Seedburo Equipment Company, Des Plaines, IL). We weight the clean sample and the debris separately and recorded moisture content from each sample using a grain moisture tester.

Data Analysis

We analyzed each site year separately and treated nitrogen rate as a continuous fixed effect and treated block as a random effect. We plotted all data for inspection to determine preliminary model selection. We analyzed the data initially in SAS (v 9.4; SAS, Cary, NC) using the GLIMMIX Procedure and the Type I sequential sum of squares ("htype=1"). Yield data in Clinton 2021 fit a distinct linear-plateau, common in nitrogen rate responses (Cai et al., 2023; Cui et al., 2009; Qiang et al., 2019). We used the nlme and nlraa packages in R to fit a mixed nonlinear model for the 2021 data (Miguez, 2021; Pinheiro et al., 2021; R Core Team, 2018). Quadratic- and linear-plateau models were fit to the data; however, the quadratic-plateau model did not converge, indicating a poor fit for the data. Within the linear-plateau model, we modeled

the random effects using a positive-definite diagonal matrix structure. We modeled the final linear-plateau to express as:

$$Y_i = \begin{cases} \beta_0 + \beta_1 x_i + \varepsilon_i & \text{if } X < X_0 \\ Y_m + \varepsilon_i & \text{if } X \geq X_0 \end{cases}$$

Where Y_i is the response variable (yield), β_0 is the intercept, $\beta_1$is the linear coefficient, x_i is the explanatory variable (nitrogen rate), ε_i is the random error, X_0 is the explanatory variable inflection point when no further increase in Y_i occurs, and Y_m is the maximum response at X_0 (plateau).

RESULTS

Field conditions

In the 2021 growing season, total rainfall was higher compared to the thirty-year historical averages for Clinton and Sandhills (Table 3.2). Precipitation was above average during June, July and August and was below average for September and October with an exception at Sandhills. Due to heavy rains following planting, Sandhills suffered seed washout, which affected stands. In Clinton, precipitation exceeded the historical average in the month of July by 17.4 cm (222%) and its total precipitation for the growing season (75.1 cm) was the highest for all locations in both years. There was no trend in annual total precipitation averaged across the state. Salisbury's total rainfall fell short of the thirty-year average and this trend was seen in 2022 for all locations.

In Clinton 2021, average monthly temperatures were consistent with the historical data except for a slightly warmer October. This same pattern is seen for this year in Sandhills and Salisbury. In 2022, temperatures across locations were in line with the historical data except for a slightly cooler October in Salisbury. In Clinton 2021, we saw significant phytotoxicity due to previous herbicide trials conducted in the same field. We believe this affected sesame yields and

overall crop development. Similarly, in Sandhills the field received S-metalochlor at planting, which we believe affected emergence and plant height. Sesame is susceptible to many herbicides. Early applications of S-metalochlor affect plant vigor, consequently, affecting yield (Sperry et al., 2016). Knowledge of previous crop history and pesticide applications is important to avoid plant injury and consequently, yield losses (Couch et al., 2017a).

Stand count

We found no effect of nitrogen rate on stand count in any of the years or locations (Figure 3.1). These results are similar to those from El Mahdi (2008), where the author tested sesame's response to five nitrogen and three phosphorus rates in a multi-year study in Northern Sudan. The author found no difference in plant density among the five nitrogen rates when the phosphorus levels were 0 and 44 kg ha^{-1}. Plant density was the highest with 22 kg P_2O_5 ha^{-1} and 44 kg N ha^{-1}. Conversely, when phosphorus level remained the same and nitrogen level increased from 44 to 88 kg ha^{-1}, plant density decreased. In variety trials conducted during the same period and locations, variety '*ES103*' produced lower stand counts than the ones observed here, with a few exceptions.

Plant height

We found no effect of nitrogen rate on plant height in all locations in 2021 and Tidewater 2022 (Figure 3.2; Figure 3.3). These results are in line with those from Shehu et al. (2010), where the authors found no difference in plant height among four nitrogen rates in a one-year nitrogen, phosphorus and potassium rate study in Nigeria. We observed a positive linear effect in Salisbury and Sandhills 2022 (Figure 3.3). In both location, as nitrogen rate increased, average plant height increased linearly; for every kilogram of nitrogen applied, plant height would increase by 0.0466 and 0.0086 cm in Salisbury and Sandhills, respectively. Malik et al. (2003)

found similar results when testing three nitrogen rates in a one-year planting pattern test in Pakistan. The authors found that their highest rate (80 kg N ha^{-1}) produced the tallest plants. El Mahdi (2008), observed taller plants (79.7 cm) with the increase of nitrogen rate. The same author observed taller plants (87.0 cm) when nitrogen and phosphorous content were 88 and 44 kg ha^{-1}, respectively. Chakraborty (2013) found a significant increase in plant height with incremental doses of N in a two-year nitrogen and phosphorus study in West Bengal, India. Noorka et al. (2011), observed similar results where the highest rate (205 kg N ha^{-1}) produced taller plants in a two-year plant density and nitrogen level study in Pakistan. Nitrogen plays a critical role in plant growth and development, it is involved in cell differentiation and elongation (Ahmad et al., 2001; Babajide & Oyeleke, 2014; Frageria & Baligar, 2005). Generally, sesame has a large root to shoot ratio, and the roots are as deep as the plants are tall (Langham, 2008; Oplinger et al., 1990). In clay soils, roots penetrate 25 cm in ten days, 50.8 cm in 24 days and 76.2 cm 50 days; in sandy soils, roots will penetrate faster and grow more profusely (Langham, 2008; Weiss, 1971).

Average capsule count

There was a significant, positive linear effect of nitrogen rate on capsule count in Clinton 2021 and Sandhills 2022 (Figure 3.4, 3.5). In Clinton and Sandhills we observed that for every kilogram of nitrogen applied, capsule count increased by 0.1495 and 0.2577, respectively. In our control, average capsule count for Clinton was 11 and for Sandhills it was 57. These results agree with the results observed by Malik et al. (2003), who reported higher capsule counts with 80 kg N ha^{-1} when compared to 40 and 0 kg N ha^{-1} in a one-year planting pattern and fertility rate study. Chakraborty (2013) also observed higher capsule count when utilizing 80 kg N ha^{-1}. Noorka et al. (2011) found similar results in a two-year population density and nitrogen rate

study in Pakistan, where the authors found that capsule count increased with added nitrogen. Their highest rate (205 kg N ha^{-1}) produced 97.65 and 106.03 capsules per plant in 2008 and 2009, respectively. Additionally, Damdar et al. (2014) found higher capsule counts as nitrogen levels increased. Nitrogen rate did not have an effect on capsule count in Sandhills 2021 and in Salisbury for both years (Figure 3.4, 3.5). Ibrahim et al. (2016) observed a higher capsule count with 90 kg N ha^{-1} and no difference between 30 and 60 kg N ha^{-1}. Similarly, Shehu et al. (2010) found higher capsule count when increasing nitrogen rate but found no difference between 75 and 112.5 kg N ha^{-1}.

Yield

In Clinton 2021, there is an initial linear increase until it reached a plateau at 109.53 kg N ha^{-1} (Figure 3.6). Prior to plateauing, the linear response indicated an increase in yield of 1.476 kg ha^{-1} for every kilogram of nitrogen applied. These results are in line with those from Shehu et al. (2010), where the authors found no difference in yield between two of their highest rates applied (75 and 112.5 kg N ha^{-1}). We observed a linear effect in Sandhills 2021, where the intercept was 608.98 kg ha^{-1} and a slope of 1.3353 kg ha^{-1}. Meaning that for every kilogram of nitrogen applied, our yield increased by 1.3353 kg ha^{-1}. Chakraborty (2013) found similar results when testing four nitrogen and phosphorus rates in a multi-year fertilizer rate study in West Bengal, India. The authors observed an increase in yield as nitrogen rate increased. Ahmad et al. (2001) conducted similar research, where yield was higher when using 120 kg N ha^{-1} compared to 0, 40 and 90 kg N ha^{-1} in a two-year study. Jan et al. (2014) obtained higher yields using 120 kg N ha^{-1} when studying the influence of planting time and nitrogen rate in Pakistan. Similarly, Noorka et al. (2011) observed higher yields when increasing nitrogen rate to 205 kg N ha^{-1} in a two-year plant density and nitrogen rate study in Pakistan. Damdar et al. (2014) obtained higher

yields when increasing nitrogen rate in a one-year study evaluating water efficiency and nitrogen levels in India. In contrast with these findings, Haruna (2011) observed a reduction in yield with the 120 kg N ha^{-1} treatment and higher yields when using 60 kg N ha^{-1}. El Mahdi (2008) also observed a reduction in yield when nitrogen rates increased and phosphorus level was zero in a fertility rate study in Sudan. In other crops, high nitrogen supply may reduce yield due to its effect on phytohormone concentrations, which ultimately affect plant development processes. Additionally, increasing nitrogen rate may increase the chance of lodging (Engels et al., 2012). Nitrogen rate did not have an effect on yield in Salisbury for both years and Tidewater 2022 (Figure 3.6, 3.7). Similarly, Ibrahim et al. (2016) observed no difference in yield among three rates (30, 60 and 90 kg N ha-1), in a one year nitrogen and phosphorus rate trial in Pakistan. El Mahdi (2008) observed that as phosphorus level increased, the authors observed no difference in yield among four nitrogen rates ranging from 22 to 88 kg ha^{-1}.

Leaf N content

In Sandhills and Salisbury 2021, we saw a positive linear effect of nitrogen on foliar nitrogen concentration (Figure 3.8). In both locations, we observed an interaction of WAP and nitrogen rate. Leaf nitrogen concentration shared the same slope (0.003204) in Salisbury, where our highest intercept was at 6 WAP and the lowest was at 12 WAP, which was not different than the 8 and 10 week mark. Similarly, in Sandhills, the slope was 0.004008, and we observed the highest concentration at 6 and 10 WAP. In Clinton 2021, we observed a significant interaction between leaf nitrogen concentration and nitrogen applied. The slopes were all positive, meaning leaf nitrogen concentration increased as nitrogen increased, however, nitrogen had a larger response at the 8 WAP mark compared to the others. We observed the same trend in 2022, were as nitrogen application increased, leaf nitrogen concentration increased (Figure 3.9). In

Salisbury, nitrogen concentration was highest at the 12 WAP and lowest at 6 WAP. In Tidewater, nitrogen had a greater effect at the 8 WAP, where leaf nitrogen concentration was highest with 224 kg N ha^{-1}. Additionally, in Sandhills, there was a greater response at the 6 WAP compared to all the other sampling times. These results are in line with Sehgal et al. (2021), were the authors tested five nitrogen treatments using Hoagland's nutrient solution in a one-year outdoor pot-culture experiment. Each treatment consisted of a reformulation of the solution ranging from 100 to 0% N. The authors found maximum leaf N concentration when Hoagland's nutrient solution contained 100% of the N in the formula. Leaf N concentration reached 5.3%, allowing maximum growth.

DISCUSSION

Although a nitrogen rate effect throughout locations was inconsistent for all agronomic traits studied, we observed a positive increase in leaf nitrogen concentration with increasing rates of nitrogen applied (Table 3.3). The slopes were all positive, meaning leaf nitrogen concentration increased as nitrogen increased. We observed a trend where N concentration was generally higher at 6 and 8 WAP, with a few exceptions. Nitrogen concentration in plants depend on genetics, environmental conditions, growth stage, and sample time (Elhanafi et al., 2019). During sesame's reproductive growth stage, which usually starts 6 WAP and lasts approximately 60 d, 31-66% of nitrogen absorbed by the plant is remobilized to capsule and seeds (Couch et al., 2017b; Langham, 2007; Langham, 2008). Overall, as nitrogen application increased, leaf nitrogen concentration increased linearly, however, this effect was not influencing other agronomic traits.

Nitrogen rate did not have an effect on sesame stand counts (Figure 3.1). In other crops such as flax (*Linum usitatissimum* L.) and canola (*Brassica napus* L.), nitrogen fertilizer

occasionally decreased stand density when side-banded (Grant et al., 2010; Grant et al., 2016). In general, fertilizer application may damage seedlings, reducing stand density due to ammonia toxicity and desiccation caused by high osmotic potential (Dowling, 1996). Additionally, stand count had no correlation with yield according to our findings in Chapter 2. Sesame utilizes excess fertility for increased vegetative growth; however, this added growth does not result in increases in yield and can actually reduce yield and seed fill due to an imbalance in nutrient source strength and remobilization (Langham, 2007). The lack of nitrogen effect in yield and growth traits in Salisbury and Tidewater might be due to higher inherit fertility in the soil. Sesame produces a large root system that is very effective at scavenging nitrogen and other nutrients (Couch et al., 2017a; Langham, 2007; Langham, 2008). It would be an effective catch crop for the leaching-susceptible southeaster U.S regions (Couch et al., 2017a). Langham (2007) hypothesized that based on a field's previous cropping history, sesame roots may pull nutrients that leached below the previous crop's root depths. Many farmers have reported adding no fertility and getting a good crop because of that deep fertility (Langham, 2008). Additionally, sesame is highly susceptible to waterlogging, and can experience a reduction in growth and yield when grown in poorly drained soil (Ucan et al., 2007). In Tidewater, we observed foliar pathogens and standing water, which affected overall plant health, resulting in early harvest, which may have confounded plant height and yield. However, as stated prior, foliar nitrogen concentration had a positive response to increases in applied nitrogen. As for several of the observations in this study, we believe that the plants began taking up more nutrient than needed, which indicates luxury consumption. There was a lack of remobilization of these nutrients to the reproductive parts of the plant, hence no effect of nitrogen capsule count in all locations except Clinton and Sandhills. In Sandhills, we observed a linear increase in yield as well as foliar

nitrogen concentration. Clinton and Sandhills have much courser, low organic matter soils, compared to the heavy clay soil in the Piedmont and higher organic-matter containing soils in Tidewater. We believe that the yield response to nitrogen observed in Clinton and Sandhills was due to lower inherent soil nutrient content as well as a higher tendency for leaching. Yields in Clinton followed a common linear-plateau model (Figure 3.6). We did not observe a yield plateau in Sandhills in either year (Figure 3.6, 3.7), which we attribute to the highly leachable soils of that region. Sandy soils are more susceptible to nitrate leaching than soils with higher clay or silt content, especially when rainfall and irrigation exceed the soil's water holding capacity (Gaines & Gaines, 1994; Couch et al., 2017a). When grown in soils similar to Sandhills, it is advised to employ practices that mitigate nitrogen loss due to leaching. Since having all the fertility up front will produce large plants with luxuriant leaves and seed production will not be as high; multiple, smaller application of nitrogen within a season is recommended (Langham, 2008).

CONCLUSION

The objectives of this nitrogen rate study were to determine optimum nitrogen levels for the different soil types and develop recommendations for North Carolina growers. The results obtained in this study were inconsistent and highly dependent on environmental factors. Additionally, this study included a single variety ('*ES103*'), which has not been the best performing variety for North Carolina (Chapter 2). This leads us to believe that the variety used may have confounded the effect of nitrogen on yield and other agronomic traits. Further work is needed to investigate the effect of nitrogen rate on different sesame genetics that may be a better fit for the region. Overall, we observed an increase in yield in some of our locations where soils were course and nutrient poor. We did not observe the effect of nitrogen in locations with higher

inherent nutrient content and less leaching capacity. This emphasizes the importance of knowledge of previous crops on that field and soil sampling, which are decision-making tools for proper crop management.

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Table 3.1 Chemistries used for weed control in sesame fields in 2021 and 2022.

Location	Time of application	Product name	Active Ingredient	Rate (g ai ha^{-1})
Clinton 2021	Preemergence	Roundup Original Max	Glyphosate	850.92[X]
	Postemergence	Dual Magnum	S-metolachlor	1,977.10
	Postemergence	Diuron 4L	Diuron	576.12
Sandhills 2021	Preemergence	Buccaneer Plus	Glyphosate	855.73
	At planting	Dual II Magnum	S-metolachlor	1,321.52
Sandhills 2022	Preemergence	Treflan	Trifluralin	691.90
	Postemergence	Dual II Magnum	S-metolachlor	1,321.52
Salisbury 2021	Postemergence	Diuron 4L	Diuron	576.12
	Postemergence	Roundup PowerMAX 3	Glyphosate	1,382.15
Salisbury 2022	Preemergence	Treflan 4L	Trifluralin	691.90
	Preemergence	Gramoxone SL 3.0	Paraquat	542.10
Tidewater 2022	Preemergence	Treflan 4L	Trifluralin	691.90
	Postemergence	Clethodim 2E	Clethodim	288.06

The chemistries used were subject to availability in each Research Station.
[X] Glyphosate reported in grams of acid equivalent per hectare.

Table 3.2 Average temperature and total rainfall by month during the sesame growing seasons in 2021 and 2022 at each research station.

Location	May		June		July		August		September		October		November		Total
	°C	Rainfall (cm)	°C	Rainfall (cm)	°C	Rainfall (cm)	°C	Rainfall (cm)	°C	Rainfall (cm)	°C	Rainfall (cm)	°C	Rainfall (cm)	Rainfall (cm)
Clinton															
2021	-[Y]	-	24.5	14.5	25.7	31.7	26.1	17.3	22.9	5.5	19.3	6.1	-	-	75.1
30 yr[X]	-	-	24.8	12.4	26.8	14.3	25.8	14.2	22.7	16.0	16.9	8.6	-	-	65.5
Sandhills															
2021	-	-	23.6	15.1	25.0	12.1	25.2	13.5	22.2	10.7	18.9	10.3	-	-	61.7
2022	-	-	24.9	7.7	26.1	10.0	24.8	9.0	21.5	13.3	15.6	1.4	-	-	41.3
30 yr	-	-	24.4	11.3	26.4	11.9	25.7	10.7	22.2	12.0	16.3	9.0	-	-	54.9
Salisbury															
2021	-	-	23.3	12.2	25.0	9.4	25.0	7.8	21.0	8.7	17.9	2.2	8.8	2.7	43.0
2022	-	-	24.4	0.8	25.7	20.7	24.1	9.4	19.8	16.1	13.3	3.1			50.0
30 yr	-	-	23.7	10.8	25.6	11.0	24.8	10.3	21.4	10.2	15.3	8.0	9.6	8.4	58.7
Tidewater											-	-	-	-	
2022	21.2	0.8	24.1	6.4	26.2	14.2	24.8	16.3	21.5	21.1	-	-	-	-	58.7
30 yr	20.2	9.8	24.4	12.6	26.4	14.8	25.6	15.8	22.8	14.9	-	-	-	-	67.9

[X] 30 year average calculated from 1990 to 2020 and collected from NOAA NCEI

[Y] Data not included for months outside the planting and harvest dates.

Weather data retrieved from the State Climate Office of North Carolina with the Cardinal Request Builder tool.

Table 3.3 Leaf nitrogen concentration intercepts and slopes for repeated measures response curves.

2021	Weeks after planting	Intercept (mg L^{-1})	Slope (mg L-1/kg ha^{-1})
Clinton	6	3.4818	0.000152
	8	2.3780	0.008455
	10	2.3370	0.003085
	12	3.0740	0.000911
Salisbury	6	5.2050 A[z]	0.003204
	8	4.2915 B	0.003204
	10	4.6120 B	0.003204
	12	4.2235 B	0.003204
Sandhills	6	4.0745 A	0.004008
	8	3.6675 B	0.004008
	10	4.0615 A	0.004008
	12	3.5865 B	0.004008
2022			
Salisbury	6	3.3810	0.001067
	8	3.3210	0.003915
	10	3.5745	0.002029
	12	3.9040	0.000653
Sandhills	6	2.9762	0.005512
	8	2.7107	0.003022
	10	2.5163	0.004455
	12	2.7926	0.001894
Tidewater	6	3.9524	0.000764
	8	3.6964	0.003505
	10	3.3467	0.004088
	12	3.1791	0.004484

[Z] Means within a location, year and weeks after planting that share a common letter are not significantly different (α=0.05).

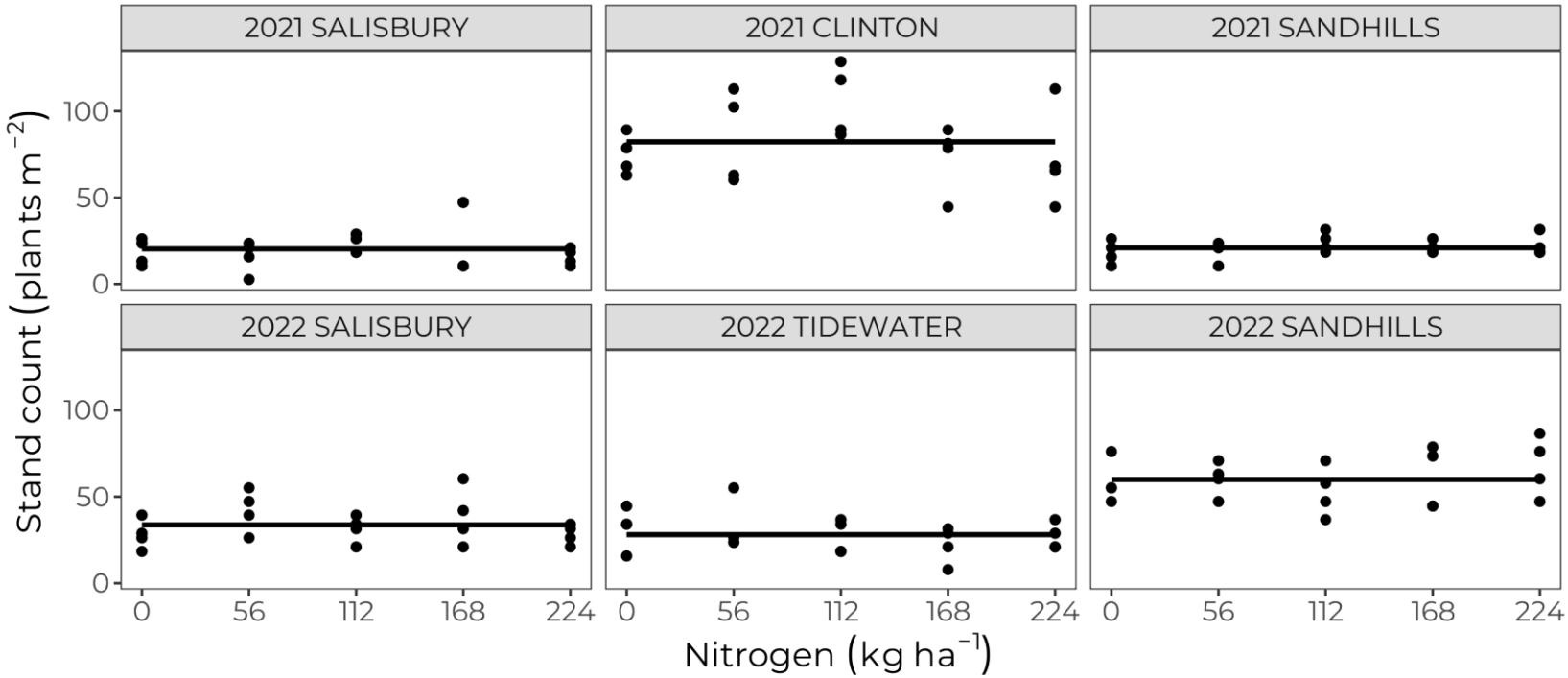

Figure 3.1 Effect of nitrogen rate on stand count in sesame grown in 2021 and 2022.

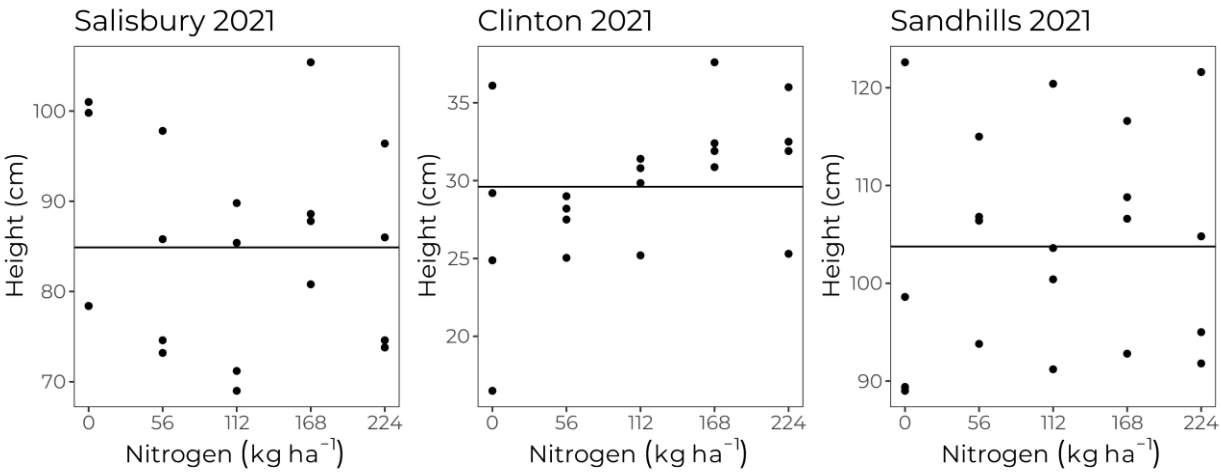

Figure 3.2 Effect of nitrogen rate on average plant height in sesame grown in Salisbury, Sandhills and Clinton 2021.

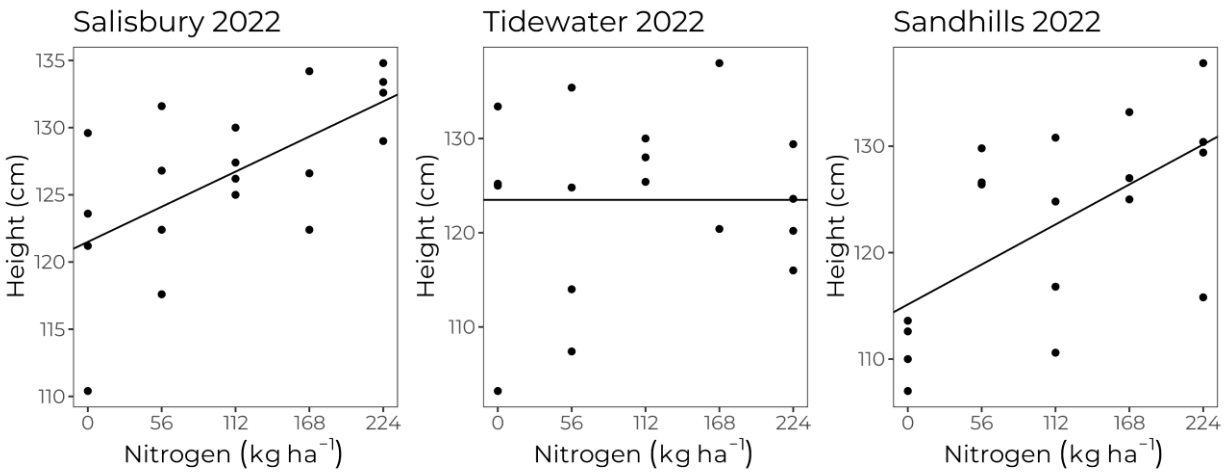

Figure 3.3 Effect of nitrogen rate on average plant height in sesame grown in Salisbury, Sandhills and Tidewater 2022.

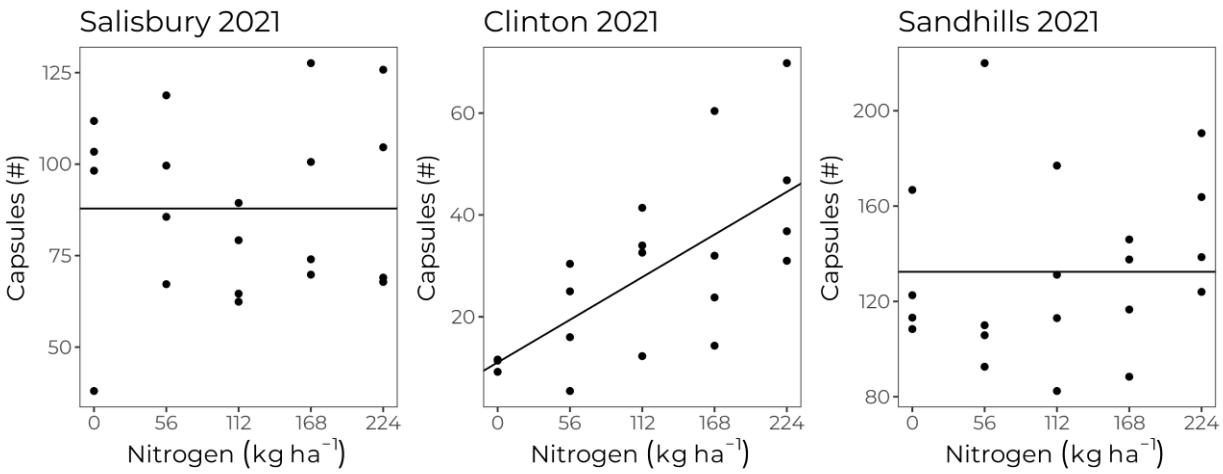

Figure 3.4 Effect of nitrogen rate on average capsule count in sesame grown in Salisbury, Sandhills and Clinton 2021.

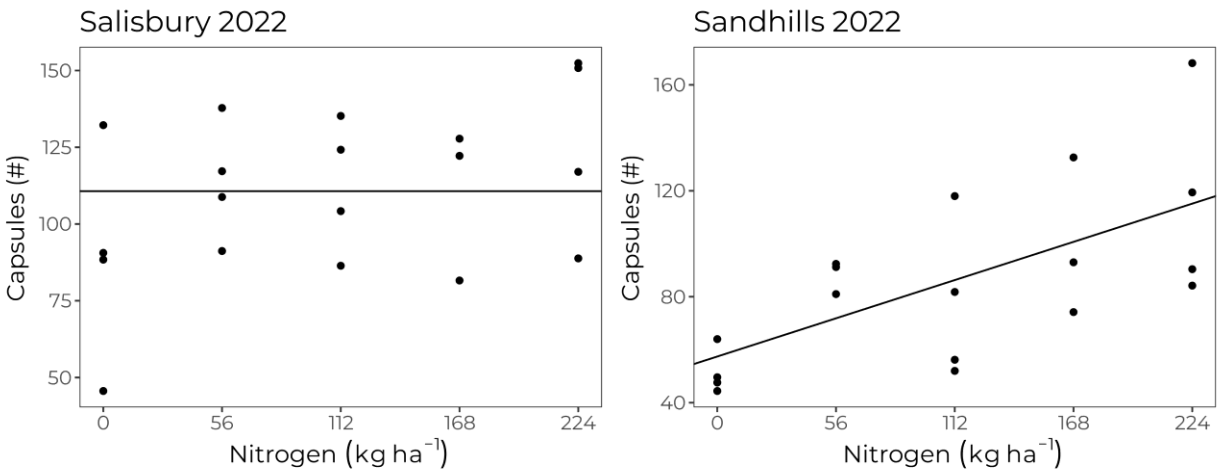

Figure 3.5 Effect of nitrogen rate on average capsule count in sesame grown in Salisbury and Sandhills 2022.

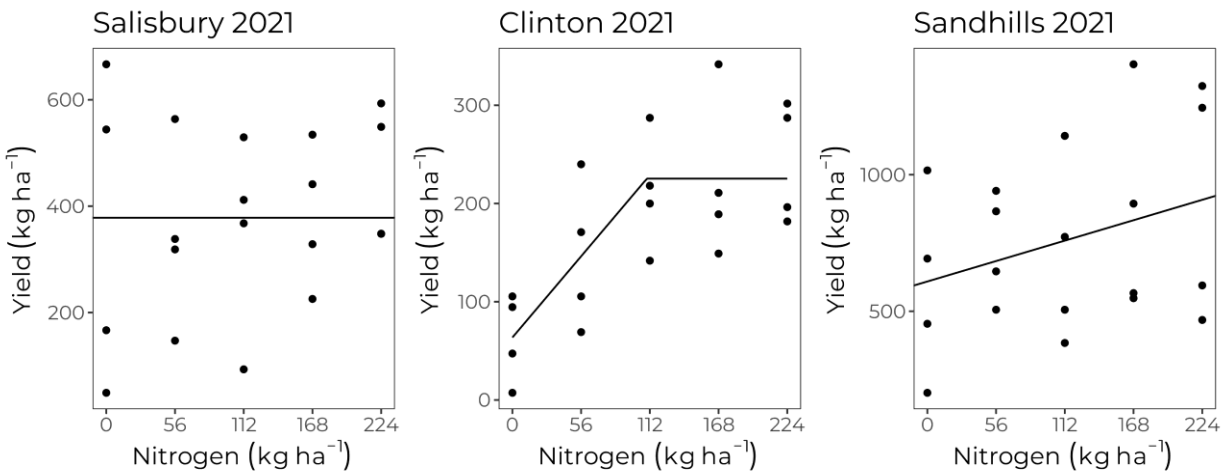

Figure 3.6 Effect of nitrogen rate on yield in sesame grown in Salisbury, Sandhills and Clinton 2021.

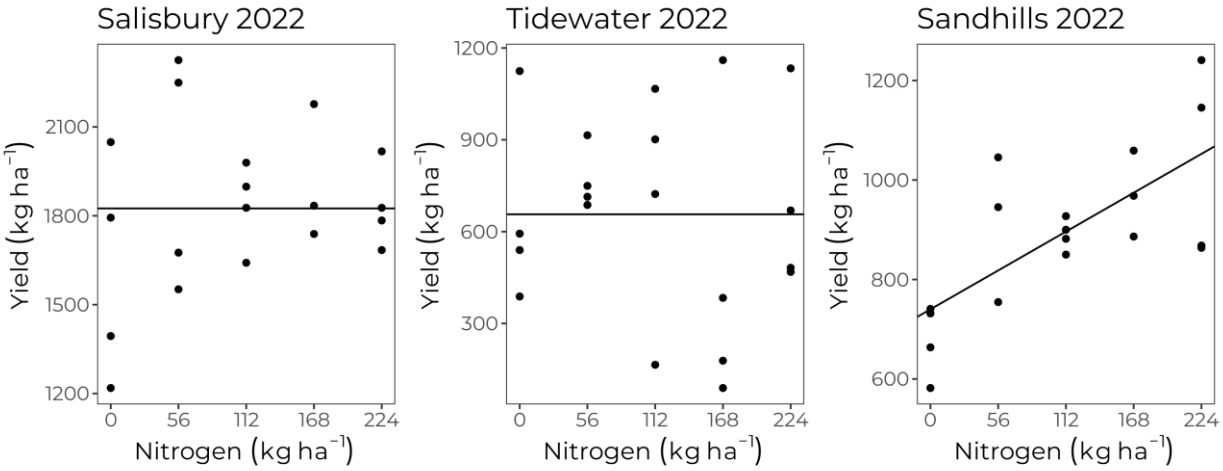

Figure 3.7 Effect of nitrogen rate on yield in sesame grown in Salisbury, Sandhills and Tidewater 2022.

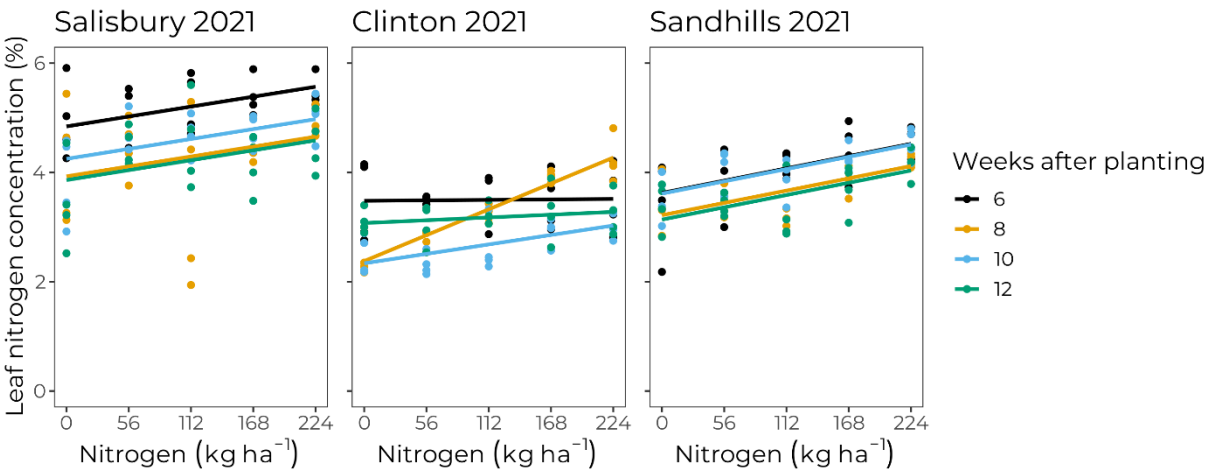

Figure 3.8. Influence of nitrogen application rate on foliar nitrogen tissue concentration from six to twelve weeks after planting in 2021.

In Salisbury and Sandhills, there was a significant ($P < 0.05$) interaction of the main effects with slope depending on nitrogen rate. In Salisbury and Sandhills, the main effects of nitrogen rate and weeks after planting was significant and in Clinton, the interaction of nitrogen rate and weeks after planting was significant.

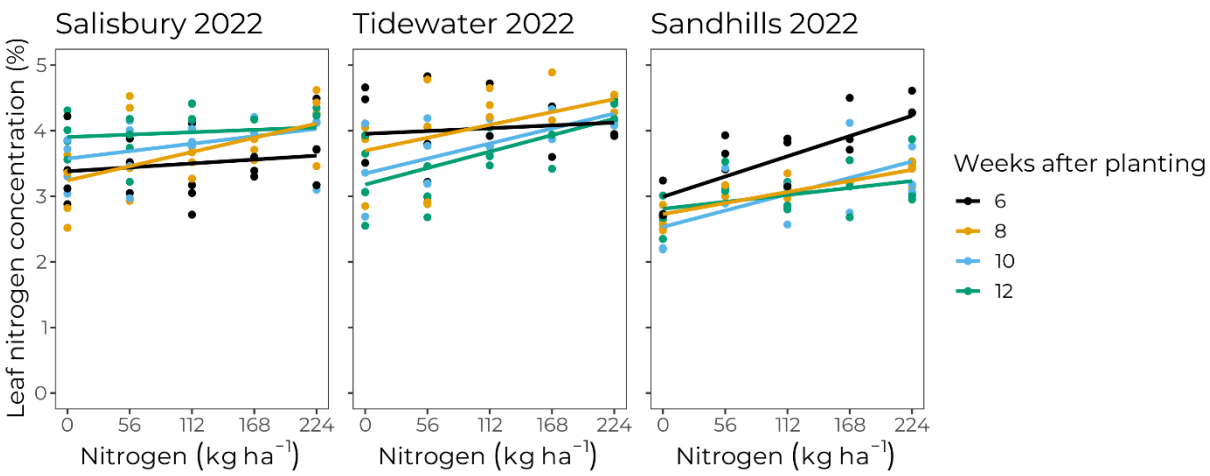

Figure 3.9. Influence of nitrogen application rate on foliar nitrogen tissue concentration from six to twelve weeks after planting in 2021.

In all locations, there was a significant ($P < 0.05$) interaction of the main effects with slope depending on nitrogen rate.

CHAPTER FOUR

Screening sesame (*Sesamum indicum* L.) for resistance to various root-knot nematode species

ABSTRACT

Root-knot nematodes (RKN; *Meloidogyne spp.*) are among the most damaging groups of plant-parasitic pests. They parasitize almost every species of higher plant and induce the formation of galls along the plant roots, which are detrimental to plant growth. North Carolina's leading field crops are sweetpotato (*Ipomoea batatas* (L.) Lam.), soybean (*Glycine max* L. Merr), cotton (*Gossypium hirsutum* L.) and tobacco (*Nicotiana tabacum* L.), which are all hosts to root-knot nematode species. This pathogen represents a major threat to farmers, obligating them to seek alternative crops that will help decrease soil populations and provide economic revenue. We tested seven sesame varieties for their host status and potential resistance to four *Meloidogyne* species (*M. arenaria, M. incognita, M. enterolobii,* and *M. hapla*). We inosculated sesame seedlings with 1,000 nematode eggs of each species. Sixty days after inoculation, we harvested the plants to evaluate a visual gall severity rating, determine a final egg count, and calculate the reproductive factor. For each sesame variety, the final egg count per root system divided by the initial inoculum, known as reproductive factor (RF = Pf/Pi) was assessed, and non-host or resistant varieties were those with an RF < 1. All sesame varieties had a significantly lower RF than the tomato control for all species of RKN, with the exception of *M. arenaria* ($P = 0.065$). Among the sesame varieties, the RF values of those inoculated with *M. incognita* and *M. hapla* were not significantly different than each other; however, there were significant differences in RF among sesame varieties inoculated with *M. enterolobii*, suggesting that genetic variability of the host may play an important role in host status and conferring resistance

INTRODUCTION

Root-knot nematodes (*Meloidogyne* spp.; RKN) are among one of the most damaging groups of plant-parasitic nematodes. These microscopic, polyphagous, obligate sedentary endoparasites have a broad host range, causing significant yield losses worldwide (Moens et al., 2009; Molinari, 2012). They parasitize almost every species of higher plant by penetrating the host's roots and inducing the formation of small to large galls or knot-like swellings along the plant roots (Gill & McSorley, 2001; Moens et al., 2009). These galls are detrimental to plant growth since they interfere with the crop's ability to absorb water and nutrients (Khan et al., 2017). Additionally, their feeding can cause early senescence, wilting, premature defoliation, stunting, and total crop loss (Khan et al., 2017; Moens et al., 2009; Perry & Moens, 2011). Under ideal environmental conditions and depending on the RKN species and host species, the life cycle of most RKN is completed in 3-6 weeks (Subbotin et al., 2021). This allows for several generations to develop during one cropping season, which can lead to a rapid increase in population and severe crop damage (Moens et al.,2009). RKN females deposit their eggs in a protective gelatinous matrix outside of the root tissue (Moens et al., 2009). Within the egg, the developing nematode will molt from the first stage juvenile (J1) to the infective second stage juvenile (J2). Hatching of the J2 is dependent on temperature and moisture, although other factors such as root exudates may modify the hatching response (Curtis et al., 2009; Moens et al., 2009; Perry & Moens, 2011). The motile J2 is attracted to the host's roots, specifically susceptible plant roots, where it penetrates at the root tip or zone of elongation (Curtis et al., 2009; Perry & Moens, 2011). After invasion, the J2 migrates intracellularly using cell wall-degrading enzymes secreted through its hollow, needle-like mouth spear, called the stylet (Perry & Moens, 2011). Once established, the RKN becomes sessile and induces immature xylem

parenchyma cells to differentiate into specialized nurse cells called giant cells, which become its permanent feeding cite (Moens et al., 2009; Perry & Moens, 2011). A sign that the J2 has become sedentary is the swelling of the root and the formation of a gall, which is visible to the naked eye (Bartlem et al., 2014; Jones & Goto, 2011). Here, the J2 will molt into a third-stage juvenile (J3) and then to the fourth-stage juvenile (J4), for which feeding is interrupted due to a lack of a functional stylet. Finally, there is a true metamorphosis from juvenile to adult female or male, where females have a globose shape and males are vermiform (Moens et al., 2009). The major species of RKN reproduce by parthenogenesis, where the progeny are "clones" of the female adult; the production of males is lower, and they do not have a sexual role (Bert et al., 2011). Depending on the species, females lay an average of 400-1,000 eggs each, this number may reach up to 2,000 eggs, which can hatch and reinfect the roots (Perry & Moens, 2011; Tunçsoy, 2021). However, with unfavorable conditions such as high population densities, unsuitable or nutritionally deficient hosts and high temperatures, females undergo a sex differentiation, developing into males (Grundler & Hofmann, 2011; Perry & Moens, 2011).

Historically, RKN management has been achieved with chemical nematicides, however, the extensive use of these chemicals pose a potential hazard to the environment and human health, which has led to a decline or ban of many of these products (Noling & Becker, 1994; Perry & Moens, 2011). Therefore, development and implementation of economically feasible and environmentally safe alternatives is required (Fernández et al., 2001; Noling & Becker, 1994). Among other management tactics is the use of crop rotation, based on the premise that monoculture of a susceptible host results in increased pathogen inoculum density (El-Nagdi & Youssef, 2015; McSorley, 1999). Additionally, crop rotation systems may introduce resistant or less suitable hosts that may either inhibit pathogen growth through not meeting the nutritional

needs of the pathogen, the production of toxic compounds detrimental to the pathogen, or support antagonistic microbial communities in the rhizosphere (Rodriguez-Kabana & Canullo, 1992; Travedi & Barker, 1986). The magnitude of nematode control attained through crop rotation will vary with the year, cultivar and resistance of the plant species, associated weed hosts, environmental conditions, and the length of the rotation (Bhan et al., 2010; Travedi & Barker, 1986).

The introduction of sesame (*Sesamum indicum*) into a cropping system has proven to reduce RKN levels effectively (Couch et al., 2017). The nematicidal (killing) and nematistic (suppressive) effect from sesame, is attributed to the lignans sesamin and sesamolin, which are natural antioxidants only found in this crop (Ashri, 1998; Bedigian & Harlan, 1986; Couch et al., 2017). These lignans have nematicidal characteristics that may help suppress RKN penetration into roots, interfering with the normal development of juveniles and change the sex ratio in favor of males (Beidigian & Harlan 1986; Tanda et al., 1988). Some researchers have observed a decrease in galling when using sesame seed extract on okra production (Kankam et al., 2015). Other benefits of including sesame into a rotation are its ability to grow under drought conditions reducing irrigation needs, improving soil quality by preventing nutrient leaching and increasing wildlife and pollinator habitat (Couch et al. 2017; Langham, 2007; Langham, 2008; Sheahan, 2014). Sesame is a relatively new crop in the US, with its production centered in Texas, Oklahoma, Arizona, and Kansas (Grichar et al., 2011; Gloaguen et al., 2018; Langham, 2007). However, production levels do not meet domestic consumption and sesame imports have been increasing over the years, reaching 37,000 tons worth $82.3 million in 2021 (Couch et al., 2017; FAOSTAT, 2023).

There is a need and interest to explore other suitable areas for sesame production, particularly the southeast United States due to its warm, long growing season, and greater annual precipitation compared to the Southwest (Couch et al., 2017; Gloaguen et al., 2018). Nematode management is critical in North Carolina (NC), where major crops such as sweetpotato (*Ipomoea batatas* (L.) Lam), cotton (*Gossypium hirsutum* L.), tobacco (*Nicotiana tabacum* L.) and soybean (*Glycine max* L. Merr), are suitable hosts for RKN. These crops are susceptible to various RKN species, including the southern root-knot (*M. incognita*), northern root-knot (*M. hapla*), peanut root-knot (*M. arenaria*) and the guava root-knot (*M. enterolobii*) (Thiessen & Rivera, 2019; Quesada, 2018). Researchers have evaluated sesame for resistance to RKN in both field studies as well as in controlled environments. Tanda et al. (1988) found no galling in sesame roots inoculated with *M. incognita*, when compared to okra.

Sesame was a poor host to RKN among 10 varieties tested; supporting low eggs counts for one RKN species (Starr & Black, 1995). Sesame rotations have proven to be effective at controlling RKN populations (El-Nagdi & Youssef, 2015; Rodriguez-Kabana et al., 1994; McSorley et al., 1994). While these RKN species pose a threat to crop production in NC, considerable attention has been given to guava root-knot nematode in recent years as it is relatively new and causes significant damage to the state's sweetpotato industry. North Carolina is the largest sweetpotato producing state, with 32,375 hectares with a production value of $225,005,000 in 2022 (USDA, 2022). The guava root-knot nematode causes severe yield loss by affecting root quality, reducing the marketable value of the produce; it also causes total crop loss in North Carolina (Brito et al., 2020; Moens et al., 2009).

With the introduction of sesame into North Carolina's agronomic rotations, it is necessary to evaluate the crops potential to suppress nematode populations utilizing the varieties

proposed for this region. The objectives of this study were to evaluate sesame's resistance to the southern root knot (*M. incognita*), northern root-knot (*M. hapla*), peanut root-knot (*M. arenaria*) and the guava root-knot (*M. enterolobii*) as well as to identify which sesame varieties may provide higher resistance to generate recommendations for North Carolina farmers.

MATERIALS AND METHODS

We conducted the nematode resistance trials at the North Carolina State University Method Road Greenhouse Complex, in Raleigh, NC 27607. We screened seven commercially available sesame varieties for resistance to four root-knot nematode species (RKN) including *Meloidogyne incognita*, *M. arenaria*, *M. javanica*, and *M. enterolobii*. Two seed companies provided the varieties used for the experiment: Equinom Ltd. (Givat Brenner, Israel) and Sesaco Corporation (Austin TX, USA) (Table 4.1). The tomato (*Lycopersicum esculentum*) cultivar 'Rutgers' was used as a susceptible control. Three sesame seeds were planted in a 3.8 cm diameter × 20 cm deep plastic container filled with a steam-sterile 1:1 (v:v) sand soil mixture. We conducted the trials twice and arranged them in a full-factorial (7 varieties × 4 RKN species) complete randomized design with six replicates. One week after planting (WAP), we carefully removed the emerged seedlings and left only one per container. We fertilized each container with 5 g of slow-release, balanced fertilizer (14-14-14 Osmocote Smart-Release Plant Food, The Scotts Company, Marysville, OH). The greenhouse was maintained at 25 to 28 °C and plants were watered twice a week in the first 7 WAP and once a week from week 8 to harvest.

Thirty DAP, which allowed the sesame plant to develop its root system, containers were inoculated with 1,000 RKN eggs by pipetting the egg solution into a 1.5 cm deep hole made into the soil at the base of each plant. We collected eggs from the four species individually from cultures maintained on 'Rutgers' tomato following the NaOCl extraction method described by

Hussey and Barker (1973). To produce the initial inoculum, roots from each infected tomato were soaked in a 10% bleach solution for 40 seconds, gently massaging egg masses from the roots. The solution was then poured through a set of sieves (from top to bottom, 250um, 75um, 25um) and rinsed with water to remove bleach residual from the eggs. We rinsed the eggs at the bottom 25um sieve with water until the tube (Falcon 50 mL centrifuge tube) was filled with 35 mL of solution. To ensure a clean sample to aid in rapid counting of inoculum density, a sucrose centrifugation step was included. We topped each tube to 50 mL with a 70% sucrose solution and centrifuged for 5 min. After centrifugation, the solution was sieved (25um) a second time and transferred into a clean 50 mL tube. Each of the four species had a specific sieve to avoid contamination. Eggs were quantified by taking three 100 ul subsamples and counting the eggs using an inverted microscope (Nikon TMS) at 40x magnification. We multiplied the average count by 10 to determine the concentration of eggs/ml.

Sixty days post inoculation, we cut the sesame and tomato control plants at the crown to separate the roots. We rinsed each root system with cold water to remove soil and recorded fresh root weight. Four plants from each treatment group were given a visual gall score based on the percent of the root system galled using a scale of 0-10, with 0 representing 0% root galling, 6 representing 50% and 10 representing 100% (Zeck, 1971; Figure 4.1). A single researcher rated for gall score. We extracted RKN eggs from the same four individual root systems using the NaOCl method described above. We took three 1 mL subsamples from each sample to quantify egg count. We multiplied the average by the tube's volume to determine the total number of eggs per root system (final population, Pf).

We calculated reproductive factor (RF) for each sample using a ratio of the final population (Pf) and the initial population (Pi). Reproductive factor values determine the

susceptibility or resistance of a plant species to nematodes. An RF value less than one indicates a poor host or non-host resistance, while values above one indicate susceptibility (Ferris et al., 1993). An RF value equal to one indicates a maintenance host, in which the population of nematodes is neither increasing nor decreasing.

We analyzed the data using the GLIMMIX procedure in SAS version 9.4 (SAS Institute, Cary, NC). When appropriate, we completed least squared mean separation using Tukey's HSD means separation at a significance of $P < 0.05$.

RESULTS AND DISCUSSION

Root gall severity

There were significant differences in visual gall severity rating between all sesame varieties and the tomato control (Table 4.2; $P < 0.0001$). Gall severity rating was significantly higher in the tomato control for all nematode species when compared to all the sesame varieties used. We observed the highest visual gall rating when inoculating the tomato control with *M. enterolobii* (6.3). Conversely, we observed the lowest gall rate from the tomato control inoculated with *M. hapla* (2.0). Rodriguez-Kabana and Canullo (1992) found similar results when testing four sesame varieties as well as other potential rotational crops for Alabama, in a pot experiment to evaluate their susceptibility to *M. incoginta*. In the first experiment, root gall indices for all the sesame varieties was 0 and in the second experiment root galling severity never exceeded 1 (Rodriguez-Kabana and Canullo 1992). McSorley et al. (1994) found similar results in a multi-year field study evaluating the effect of crop rotation on fields infested with *M. incognita* and *M. arenaria*. The authors found no galls in sesame roots and a low gall index (0.2) for 'Lemondrop L' squash (*Cucurbita pepo* L.) roots. Conversely, the sesame rotation with eggplant (*Solanum melongena* L.) produced a larger gall index (3.3) in a scale of 0-10 (Taylor &

Sasser, 1978). The degree of root galling generally depends on the RKN population density, RKN species, susceptibility of the host species, and environmental conditions (Chandra et al., 2010). Root galls are visible 30 to 35 days after emergence, but are small at early vegetative growth stage, becoming larger as plants flower. Galling becomes more extensive as multiple nematodes establish a feeding site in a single root (Faske et al., 2021). Sesame root cells secrete chemical metabolites that may be toxic to nematodes, inhibiting penetration and motility, which ultimately has a negative effect on population density; hence, the lack of visible root galls (Araya & Caswell-Chen, 1994; Tanda et al., 1988).

Eggs per root system

There were significant differences in total eggs per root tissue among the tomato controls and sesame varieties investigated inoculated with *M. enterolobii, M. hapla* and *M. incognita* ($P < 0.0001$; Table 4.3). There were no significant differences among sesame varieties inoculated with *M. hapla* and *M. incognita*, but all sesame varieties had significantly lower egg populations than the tomato control. The tomato control inoculated with *M. incognita* had the highest amount (27,492 eggs/root system) compared to the other three species. We found differences among the sesame varieties inoculated with *M. enterolobii* (Table 4.3). Variety '*ES103*' had the lowest population (148 eggs/root system) but was not different from varieties '*ES107*', '*ES108*', '*S3276*', '*S3251*' and '*S3301*'. Variety '*S39*' had the highest population (1,627 eggs/root system) of all sesame varieties but was still less than the tomato control, which had a 6,740 eggs/root system. Females lay an average of 400 to 1,000 eggs, which depending on the environmental conditions will hatch and reinfect the host's root (Perry & Moens, 2011; Tunçsoy, 2021). RKN life cycle is completed in 3 to 4 weeks, which means there are several generations in one cropping season (Moens et al., 2009). These results are in line with Starr and Black (1995),

where the authors tested 10 sesame varieties in a pot experiment and found no reproduction of *M. incognita* in all but two varieties. In the present study, there were no differences among varieties inoculated with *M. arenaria* ($P = 0.0693$; Table 4.3). We attribute this to the high level of variability found in the data. Starr and Black (1995) tested two sesame varieties in the field and found *M. arenaria* egg counts to be no greater than 40 eggs/500 cm^3 of soil compared to the susceptible peanuts that had a mean population density of 2,490 eggs/500 cm^3 of soil. Conversely, the same authors found that sesame supported a limited reproduction of *M. arenaria*, ranging from 50 to 1,570 eggs/g root, in their greenhouse study. This variation in reproduction suggests that some sesame varieties support greater nematode populations of a particular species compared to others. Additionally, unfavorable or nutritionally deficient hosts may cause females to undergo a sex differentiation, developing into males, which are not required for RKN reproduction (Bert et al., 2011; Grundler & Hofmann, 2011; Perry & Moens, 2011).

Reproductive factor

There were significant differences in RF among plants inoculated with *M. hapla*, *M. enterolobii*, and *M. incognita* ($P < 0.0001$; Table 4.4). The RF for the tomato control was 3.72 and 27.50 for *M. hapla* and *M. incognita*, respectively. We found differences in RF among sesame varieties and the tomato control inoculated with *M. enterolobii*. Variety '*ES103*' had the lowest RF (0.15), but was not different from varieties '*S3301*', '*ES107*', and '*ES108*'. Variety '*S39*' had the highest RF (1.63) from all sesame varieties, but was not different from varieties '*S3276*' and '*S3251*'. This indicates that resistance may be genetically controlled. El-Nagdi and Youssef (2015) obtained similar results in a field study evaluating several rotational crops with sugar beet (*Beta vulgaris*). The authors found sesame to be effective at lowering RKN populations, since they obtained a reproductive factor of 0.01 for *M. incognita*. During the RKN

life cycle, the motile J2 is attracted to the host's roots, specifically susceptible plant roots, where it will establish its feeding cite (Curtis et al., 2009; Perry & Moens, 2011). Hatching of RKN eggs is dependent on temperature, sufficient oxygen levels and moisture, although other factors such as root exudates may modify their hatching response (Curtis et al., 2009; Moens et al., 2009; Perry & Moens, 2011). Sesame root exudates contain lignans that inhibit nematode penetration and motility, thus decreasing reproduction rates and development (Araya & Caswell Chen, 1994). Although numerically different, the degree of variability observed in the RF values for the *M. arenaria* inoculated plants was too great to find significant differences ($P = 0.0649$).

CONCLUSION

The objective of this greenhouse study was to evaluate the host status of sesame varieties to multiple RKN species. The results obtained in this study are comparable to those found in the literature, where sesame has shown to suppress and lower nematode populations. Additionally, the varieties used in this study are different from any in the literature available. The number of eggs per root system was significantly lower for all sesame varieties compared to the control, except for *M. arenaria*. All sesame varieties supported a low reproductive factor for *M enterolobii*, *M. hapla* and *M. incognita*, which remained below the threshold for non-host resistance, with a few exceptions. Since there are significant differences among sesame varieties inoculates *M. enterolobii*, we can infer that relative host status and resistance may be genetically linked. We need to evaluate the suppressive effect of sesame under field conditions, especially those fields infested with *M. enterolobii*. It is unlikely that a rotation with sesame will completely eradicate nematodes from heavily infested fields or eliminate the need for nematicides altogether; however, knowledge of the poor-host status of many sesame varieties to several RKN species adds another powerful tool to the integrated pest management toolbox, and

ultimately improve farmer economics and sustainability. We would recommend to use variety '*ES103*' and '*ES108*', for farmers struggling with *M. enterolobii, M. hapla,* and *M. incognita*, since the data showed low RF values for these species. Additionally, we would recommend the use of other varieties such as '*S39*' and '*S3276*', which produced low RF values when inoculated with *M. incognita*. Overall, the use of sesame, regardless of the variety, produced low RF values to three of the four nematode species tested in this study. We would recommend the use of sesame to farmers seeking to reduce *M. enterolobii, M. hapla*, and *M. incognita* populations.

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Table 4.1 Sesame varieties used to screen for RKN resistance.

Company	Variety
Equinom	ES103
Equinom	ES107
Equinom	ES108
Sesaco	S39
Sesaco	S3301
Sesaco	S3251
Sesaco	S3276

Table 4.2 Visual gall rating for sesame varieties inoculated with 1,000 nematode eggs.

	Meloidogyne Species			
Variety	*M. enterolobii*	*M. arenaria*	*M. hapla*	*M. incognita*
	Gall rate[Y]			
ES103	0.6 b [Z]	0.4 b	0.0 b	0.0 b
ES107	1.0 b	0.1 b	0.0 b	0.0 b
ES108	0.7 b	1.0 b	0.0 b	0.1 b
S39	0.8 b	0.1 b	0.0 b	0.0 b
S3276	0.9 b	0.4 b	0.1 b	0.0 b
S3251	0.3 b	0.6 b	0.0 b	0.0 b
S3301	1.4 b	0.7 b	0.0 b	0.1 b
Tomato control	6.3 a	2.6 a	2.0 a	5.0 a
p-value	<0.0001	<0.0001	<0.0001	<0.0001

[Z] Means sharing a common letter within specie are not significantly different ($p>0.05$)
[Y] Visual gall rating was determined by observing the percent of galls present per root system and assigning the rate using the scale proposed by Zeck (1971). Rating was performed by one single researcher.

Table 4.3 Effect of sesame variety on nematode population sixty days after inoculation.

	Meloidogyne Species			
Variety	*M. arenaria*	*M. enterolobii*	*M. hapla*	*M. incognita*
	Population (eggs/root system)			
ES103	680.42	147.50 d[Z]	117.83 b	38.54 b
ES107	258.48	466.12 cd	1,046.25 b	32.08 b
ES108	622.22	155.00 cd	73.54 b	133.92 b
S3276	1,223.24	713.96 cd	693.75 b	84.92 b
S3251	443.24	750.42 cd	40.00 b	204.33 b
S3301	955.24	427.17 cd	116.58 b	231.25 b
S39	1127.42	1,627.00 b	177.17 b	39.29 b
Tomato control	4,086.24	6,739.83 a	3,723.70 a	27,492.00 a
p-value	0.0693	<0.0001	<0.0001	<0.0001

[Z] Means sharing a common letter within species are not significantly different (p>0.05).

Table 4.4 Reproductive factor for sesame varieties inoculated with 1,000 nematode eggs.

	Meloidogyne Species			
Variety	*M. arenaria*	*M. enterolobii*	*M. hapla*	*M. incognita*
	Reproductive factor (*Pi/Pf*)[Y]			
ES103	0.68	0.15 a[Z]	0.12 a	0.04 a
S3301	1.01	0.43 ab	0.12 a	0.23 a
ES107	0.31	0.47 ab	1.05 a	0.03 a
ES108	0.81	0.16 ab	0.07 a	0.13 a
S3276	1.28	0.71 bc	0.69 a	0.08 a
S3251	0.44	0.75 bc	0.04 a	0.20 a
S39	1.13	1.63 c	0.18 a	0.04 a
Tomato control	3.96	6.74 d	3.72 b	27.50 b
p-value	0.0649	<0.0001	<0.0001	<0.0001

[Z] Means sharing a common letter within specie are not significantly different (p>0.05)
[Y] Reproductive factor (RF) is the initial nematode population at inoculation over the final population collected 60 days after inoculation. RF values < 1 indicate a poor host or non-host resistance, while values > 1 indicate susceptibility.

Figure 4.1 Gall score of 0 in a sesame root system (a) and gall score of 5 in a tomato root system (b).