

**Optimizing Corn and Cotton Performance with Adaptive Management Systems and  
Subsurface Drip Irrigation in the Mid-Atlantic USA**

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Keywords: Adaptive Corn Management Systems, Subsurface Drip Irrigation (SDI) System,  
Fertigation, Plant Growth Regulators (PGR)

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## **Abstract**

Corn (*Zea mays L.*) and cotton (*Gossypium hirsutum*) are globally important crops for food, feed, fuel, and industrial feedstocks. In Eastern Virginia, achieving optimal yields is challenging due to unpredictable environmental conditions which impact overall crop growth and nutrient use efficiency. More data are needed on adaptive corn management strategies that focus on increasing nutrient use efficiencies and crop yields (i.e., 4R nutrient management, biostimulants, and in-season crop protection chemicals). With less than 5% of Virginia's corn and cotton fields irrigated, increased irrigation adoption could stabilize/increase crop production outcomes in this region. Three studies were conducted to evaluate these management strategies with the following objectives:

1. To compare standard farmer practices with the Adaptive Corn Management System (ACMS) using a treatment omission/addition approach.
2. To analyze subsurface drip irrigation (SDI) effects on corn grain yield under different seeding and nitrogen (N) application rates in drought-prone soils of Eastern Virginia.
3. To evaluate SDI strategies in cotton, assessing the effects of dripline spacing, plant growth regulator (PGR) rates, irrigation strategies, N rates, and variety on yield.

The first study integrated irrigation, in-season nutrient supplementation (soil and foliar applied), foliar fungicides, and biostimulants to enhance corn yields. Field trials conducted across five Virginia locations (2022 to 2023) with irrigated and non-irrigated sites showed yield improvements with supplemental nutrients, biostimulants, and fungicides in 4 of 10 experiments.

The yield increase resulting from irrigation in intensive and standard management strategies ranged from -3 to 61%, averaging 8.9 and 34% for intensive and standard management practices, respectively.

The second study (2022-2024) evaluated six SDI management strategies, four seeding rates (59,280 to 103,740 plants ha<sup>-1</sup>), and four N application rates (133 to 333 kg N ha<sup>-1</sup>). Main effects of irrigation, seeding, and N rates significantly impacted yields. Irrigation and N interactions were significant across years for grain yield. Corn grain yield was greater by 102% with irrigation in 2022 compared to only 13%, and 51% in 2023 and 2024. Averaged over the three years the 0.91 m dripline and 0.91 m with volumetric water content (VWC) sensors increased revenue by \$985 and \$885 ha<sup>-1</sup>, respectively, above non-irrigated. Grain yield increased up to a seeding rate of 88,920 plants ha<sup>-1</sup> and N rates up to 267 kg N ha<sup>-1</sup>.

The third study utilized two experiments evaluating SDI management strategies in cotton from 2019 - 2021. Experiment 1 of the third study tested three irrigation systems with various dripline spacings (0.91 m, 1.82 m, non-irrigated), four PGR rates (0%, 100%, 150%, 200% of current Virginia recommendations, and four cotton varieties. Experiment 2 examined three irrigation strategies (irrigation, fertigation, and non-irrigated), three N rates (89, 133, 178 kg ha<sup>-1</sup>), three PGR rates (0, 100 and 200%), and two cotton varieties. Results from experiment 1 showed that dripline spacing significantly influenced lint yields in 2 of 3 years. The PGR application rates significantly influenced lint yield in 2021 growing season only. Lint yield varied by variety in 3 of 3 years of the study. The 1.82 m dripline and 100% PGR rate produced the highest economic gains of \$158 and \$162 ha<sup>-1</sup> respectively above check. In Experiment 2, the lint yield varied by irrigation all three years, while PGR rates, N application rates, and variety each influenced lint yield in 2 of 3 years. The highest rates of lint yield increase were achieved at

133 kg N ha<sup>-1</sup>.

Irrigation implementation was more effective increasing corn grain yields than cotton lint yields during the six-year study period. Corn grain yields were increased on average 60% with SDI compared to non-irrigated treatments over the three-year study. Inputs for adaptive corn management systems were not consistent for increasing grain yields. Although various PGR rates were evaluated, current PGR recommendations for cotton are sufficient with the varieties evaluated in maximizing lint yields. The current N applications for Virginia were in-line with those of the current study which identified 133 kg N ha<sup>-1</sup>. These studies provide the first data for corn and cotton management with SDI in Virginia and the Mid-Atlantic USA.

**Keywords:** Adaptive corn management, Standard management, Intensive management, Subsurface drip irrigation (SDI), Dripline spacing, Fertigation, Plant Growth Regulators (PGR), Cotton Varieties

# **Optimizing Corn and Cotton Performance with Adaptive Management Systems and Subsurface Drip Irrigation in the Mid-Atlantic USA**

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## **General Audience Abstract**

Corn (*Zea Mays L.*) and cotton (*Gossypium hirsutum*) are essential crops globally, providing food, feed, fuel, and industrial materials. In the U.S., 36.7 million hectares of corn and 4.52 million hectares of cotton are grown annually, with Virginia cultivating 186,234 hectares of corn and 36,800 hectares of cotton. Most of these crops in Virginia are grown without irrigation on sandy soils with low nutrient and moisture retention coupled with regions non-uniform precipitation with heavy summer/fall rains which reduce nutrient efficiencies and destabilize yields. While practices like in-season nutrient application (4-R strategy), fungicides, and biostimulants can improve yields, they are not common practices in Virginia. For these practices to be part of adaptive corn management systems, their effectiveness under local conditions needs to be evaluated. The limitations to irrigation in Virginia are largely due to farmers reliance on high annual precipitations, and state restrictions on water withdrawals, desiring that any irrigation system to be adopted to be efficient and flexible for deficit irrigation. Making the SDI the better choice but for it to be adopted, more information is needed. Additionally, understanding how factors like irrigation, seeding rates, plant growth regulators (PGRs), and modern cotton varieties interact with nutrient management under the sub-surface drip irrigation (SDI) system is essential for improving productivity and sustainability of these crops.

This research aimed to develop advanced corn and cotton production systems for Virginia by addressing these challenges and evaluating effective crop management strategies.

- 1) To compare standard farmer management practices (control) and intensive management

(attempting to address common yield-limiting factors) with the ACMS using a treatment omission/addition experiment (study one).

2) To assess the impact of subsurface drip irrigation (SDI) strategies on corn grain yield in Virginia and analyze how different seeding and nitrogen (N) rates affect yield under different subsurface drip irrigation strategies in drought-prone soils of Eastern Virginia (study two).

3) a) To evaluate the effects of different dripline spacings and plant growth regulator (PGR) rates on the growth and yield of various cotton varieties,

3) b) Assess the influence of different irrigation strategies, N rates, PGR rates, and modern upland cotton varieties on yield and quality (study three).

The first study found that adding biostimulants, foliar fungicides additional phosphorus and potassium and additional sidedress nitrogen variably increased corn grain yield in 3 out of 10.

The significant differences between standard and intensive management were observed in 3 of 10 experiments. Addition of extra P and K, sidedress N, and biologicals to the standard management under the non-irrigated conditions resulted in a 15% relative yield increase compared to the irrigated conditions. On average, irrigation increased grain yields by 8.9% under intensive management and 34% under standard management, with yield improvements ranging from -3% to 38% and 14% to 61%, respectively, over non-irrigated fields.

In the second study, grain yield was significantly influenced by main effect of irrigation, nitrogen, and seeding rates with notable interactions between irrigation and nitrogen across the years (2022-2024) at  $P \leq 0.1$ . The highest impact of irrigation was observed in 2022 with yield increase up to 102% over non-irrigated compared to only 13%, and 51% in 2023 and 2024 respectively. Over the three years of this study, the grain yield gains were greatest when a 0.91 m dripline spacing was used which averaged 4,106 kg ha<sup>-1</sup> above non-irrigated yielding an

economic gain of \$985 ha<sup>-1</sup>.

Results from study one of the third experiment which evaluated the effects of upland cotton cultivars, irrigation, and PGR rates on lint yield, showed significant differences in lint yield due to variety across three years. Irrigation influenced lint yield in 2 of 3 years (2020 and 2021), while PGR rates caused yield variation only in 2021. Averaged over three years, the highest yields gains were observed using a 1.82 m dripline, and 100% PGR rate, yielding \$158 and \$162 in economic gains above the respective checks. In the second experiment of the third study, lint yield varied by irrigation treatments in all the three years, while PGR, N application and variety, each influenced lint yield only 2 of the 3 years of the study. The highest increase in yield due to N application rates was attained at 133 kg N ha<sup>-1</sup> with no statistically significant results observed at 279 kg N ha<sup>-1</sup> when compared to 133 kg N ha<sup>-1</sup>. With the exception of interaction between irrigation and variety in experiment 1 (2021), and PGR rates and N rates in experiment 2 (2021), no other significant interactions were observed for lint yield.

The findings from the study one showed that balanced N, P, and K supplementation, alongside biostimulants and fungicides could maximize corn yields in dynamic farming conditions.

Irrigation was the major driver to yield advancement.

The results from the second and third study showed that subsurface drip irrigation (SDI), particularly with a 0.91- m dripline spacing, can significantly improve corn yield, while 1.82 m dripline can enhance the cotton yield in Virginia and the mid-Atlantic. It was not economical to increase the PGR application rates beyond the 100% PGR rate of the recommended Virginia Cooperative Extension (VCE). Additionally, optimized irrigation, PGR management, and precise nitrogen application are key to achieving high yields in modern cotton varieties, ensuring efficient and resilient production system

## **Dedication**

I dedicate this work to my parents, siblings, and friends, whose unwavering support has been my foundation.

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## 1.0. General Introduction

Corn (*Zea mays* L.) and cotton (*Gossypium hirsutum*) are significant crops globally, cultivated for their diverse applications in food, feed, fuel, and industrial feedstocks. In the United States, corn and cotton cover an area of 36.7 and 4.52 million hectares respectively, making two of the larger acreage commercial crops (Meyer et al., 2023; USDA-NASS, 2024). The State of Virginia averaged 186,234 hectares of corn, and 36,800 hectares of cotton in 2024 (USDA-NASS, 2024). Previous technological advancements have seen linear increases in the yield of corn and cotton (1950-2015) (USDA-ERS, 2019). There is a large hypothetical yield gap for corn in Virginia with recorded state average yields of 10,042 kg ha<sup>-1</sup> (2021-2023) being 892 kg ha<sup>-1</sup> lower than the national average (10,934 kg ha<sup>-1</sup>) and up to 28,609 kg ha<sup>-1</sup> compared to the highest National Corn Growers Association (NCGA) yield contest entry of 2022 (AgWeb, 2023; VCA, 2023, USDA-NASS, 2024).

Much of the yield gap in Eastern Virginia is largely attributed to unpredictable weather patterns that disrupt effective farm management practices. For example, heavy rainfall during the summer/fall often coincides with nutrient applications, particularly in the region's sandy soils, with lower CEC. These conditions exacerbate nutrient loss through leaching, and denitrification, significantly reducing nutrient availability for crops and overall efficiency of nutrient use (Reiter et al., 2018). While seasonal nutrient supplementation through several sidedressing or foliar applications, along with biostimulants and fungicides can enhance yields, these practices are not widely adopted in Virginia, necessitating further investigation. Research indicates that targeted application of potassium under deficient soil conditions at critical growth stages of corn can increase corn grain yield (Charbonnier and Ruiz Diaz, 2021). A study by Wise et al. (2019) reported yield gains with foliar fungicides in the North Great Plains (NGP). Despite these

advancements, there is still a notable gap in understanding: no existing research that has evaluated all key nutrients for plant growth with other yield limiting factors and their interactions in corn production. This highlights the need for in-depth studies to evaluate the effectiveness of nutrient and input management strategies across varying conditions. Therefore, the first study employs omission/addition methodology to evaluate key nutrients and inputs under standard and intensive management practices.

Projections on climate variability suggest a 1.5°C rise in average temperatures by 2050, which may exacerbate heat and moisture stress effects, diminishing water availability for production (Nguyen et al., 2023). Therefore, effective drought mitigation strategies are essential for maintaining production and profitability. Currently, the adoption of irrigation in Virginia is limited, with only less than 5% of corn and cotton farmlands irrigated. Expanding irrigated areas could enhance yields on sandy soils in Eastern Virginia. Challenges such as restrictive water withdrawal policies and reliance on over 1,200 millimeters of annual precipitation hinder expansion of irrigation (USDA-NASS, 2023; VA-DEQ, 2024; Shortridge, 2017). Additionally, the diverse Virginia cropping systems characterized by small farm sizes, irregular shaped fields and varying terrain makes it difficult to install efficient irrigation systems. These conditions limit the expansion of the traditional irrigation methods such as the center pivot system.

The subsurface drip irrigation (SDI) presents a viable solution, enabling efficient and flexible water use in deficit irrigation scenarios (Lamm et al., 2009). The SDI system delivers water directly to the crop rootzone reducing potential water losses through evaporation. Despite higher initial installation costs compared to the center pivot systems, the superior profitability associated with SDI systems potentially offsets these expenses. With a lifespan of 20 to 25 years,

SDI remains an economically attractive option for farmers, ensuring long-term returns on investment (Lamm and Rogers, 2014, Lamm et al., 2009).

The United States has long been a leader in cotton production, ranking 2<sup>nd</sup>, to 3<sup>rd</sup> globally and holding the top spot for exports (Meyer et al., 2023). Despite a strong national average lint yield of 1,059 kg ha<sup>-1</sup>, compared to the global average of 792 kg ha<sup>-1</sup>, improving nitrogen efficiency, and yield remains essential to further enhance profitability (Meyer et al., 2023). Managing fertility in cotton is very complex as it is affected by the interaction of genetics, management, and environment (Main et al., 2013, and Main et al., 2014). Cotton, when grown using high nitrogen rates coupled with high soil moisture can result in high vegetative growth which increases the rates of PGR required to regulate its growth and improve harvest efficiency. Additionally, such conditions increase the risk of boll shedding and reduce yields. Conversely, inadequate nutrients and moisture can negatively impact growth and yield-related agronomic traits (Wu et al., 2023). Modern cultivars have been developed to respond more effectively to inputs, prompting a need to revise traditional nutrient recommendation methods (Main et al., 2014). However, there has been limited research on integrating nutrient management (such as nitrogen), PGR, and irrigation practices particularly the SDI to optimize cotton performance. Additionally, not much information is available in Virginia concerning the SDI system's impact on cotton response to nitrogen, and PGR usage, due to the fact that it has not been studied extensively in the Mid-Atlantic region.

The adoption of these management practices in the SDI system on corn and cotton in Virginia requires information on how it impacts seeding rates, nitrogen rates, fertigation, and irrigation rates (dripline spacings), and cotton variety selection, and plant growth regulator use. Therefore, the 2<sup>nd</sup> and 3<sup>rd</sup> chapters of this research employed the split-split plot layout to study

the effectiveness of SDI strategies in corn and cotton production in Virginia. The second study focused on dripline spacing, seeding rates and nitrogen rates in corn. The third research focused on dripline spacings, fertigation, nitrogen rates, modern upland cotton varieties, and PGR rates and their interactions on cotton lint yield. The overall goal of these studies was to support farmers adaptive learning to refine corn and cotton nutrient management, and to provide recommendations for SDI adoption in Virginia and the Mid-Atlantic region to improve profitability of corn and cotton. To answer these questions, three research experiments were conducted with the following objectives.

1. To compare standard farmer practices (control) to intensive management (inputs supplied to address yield limiting factors) practices in enhancing yields of corn using an omission/addition method (study one).
2. To assess the impact of subsurface drip irrigation strategies on corn grain yield in Virginia and evaluate the influence of seeding, and N application rates on corn grain production in drought-prone soils in the Mid-Atlantic region of USA (study two).
3. To evaluate the combined effects of SDI, nitrogen management, PGRs, and modern upland cotton varieties on yield, and to identify the most cost-effective irrigation system for cotton (study three).

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## **2.0. Adaptive Corn Management Systems (ACMS) for Optimizing Agronomic Performance in the Mid-Atlantic U.S.**

### **Abstract**

Corn yield is a function of complex factors which make achieving optimum yield difficult due to unforeseen factors such as losses from diseases, unpredictable weather, and varying nutrient use efficiencies. We hypothesize that irrigation, in-season nutrient supplementation, inclusion of foliar fungicides and biostimulants as a package can increase corn yield in Virginia compared to current “standard” corn management practices. This study assessed the impact of early-season biostimulants and mid-season nutrient supplementation through applications of phosphorus (P), potassium (K), and nitrogen (N), at V7, along with foliar fungicides and foliar N applied at the R1 corn growth stage. Using an addition/omission design, the research compared “standard” management with “intensive” corn management practices to identify yield-limiting factors for recommendation in an adaptive corn management system (ACMS). Field experiments were conducted in Virginia in 2022 and 2023 using a randomized complete block design at five locations. Each location had two experiments (irrigated and non-irrigated) for a total of 10 site-years. Data from these experiments were analyzed using the analysis of variance performed in JMP®, Version 18 (SAS Institute Inc., Cary, NC, 1989-2023) software and Dunnett’s test was used to compare means. Application of Biostimulants (+Biological), foliar fungicides (+Headline), supplemental P and K (+P and K), and sidedress N (+Sidedress N) increased grain yields over the standard management control in 3 of 10 experiments. Response to irrigation using intensive management practices for grain yield ranged from -6 to 38%, compared to 14 to 61% under standard management practices respectively.

Overall, the response to treatments were sparse and inconsistent among management levels and across sites/years.

**Core ideas:**

- Supplemental mid-season sidedress with N, P and K at V7, integrated with foliar fungicides and biostimulants, variably increased grain yield in standard management compared to standard management check.
- Omitting individual intensive management inputs from the intensive check resulted in limited impact on grain yield.
- The impact of irrigation was lower -6 to 38% under intensive management practices, compared to 14 to 61% under standard management practices respectively.

## 2.1. Introduction

Corn (*Zea mays* L.) is a significant crop globally, cultivated for its diverse applications in food, feed, fuel, and industrial sectors. In the United States (USA), corn is planted on 36.7 million hectares, making it one of the most widely grown commercial crops (NASS, 2024). In Virginia, corn covered an average production area of approximately 186,234 hectares in 2024 (USDA-NASS, 2024). The utilization of technological innovations in hybrid seed development, herbicides, genetic modifications, resulted in significant improvements in corn grain yield in the past years (NASS, 2022, 2023; Bowler, 2014). Despite the progress made, a significant hypothetical yield gap persists in Virginia. Among the factors contributing to the large yield gap in Virginia corn is weather and soils (Rathore et al., 2024). Virginia is often subject to sporadic droughts and or heavy summer/fall rains coinciding with major parts of the season that directly impact yield (Rathore et al., 2024). The heavy rains result in nutrient losses and reduce the efficiency of the applied nutrients (Reiter et al., 2018). These conditions demand that corn producers continually evaluate strategies to stabilize and increase yield.

Several strategies have been shown to increase corn yield, including adoption of new fertilization strategies, irrigation, use of biostimulants/growth regulators (biologicals), and application foliar fungicides (Ruffo et al., 2015; Rathore et al., 2024; Sible and Below, 2023; Wise et al., 2019). Generally, weather and nitrogen (N) management accounts for the greatest yield variability in corn (Ruffo et al., 2015, Rathore et al., 2024). This is because weather is associated with many factors that influence growth and yield of corn. For example, weather is at the center of the plant disease development with greater rainfall often resulting in greater disease pressure (Li et al., 2019).

Proactive measures such as in-season nutrient supplementation can increase nutrient availability to replace any lost nutrients (Reiter et al., 2018; Ruffo et al., 2012). Irrigation can alleviate the abiotic stress associated with rainfall deficit (Rathore et al., 2024). The use of biostimulants can reduce plants stress and increase yield (Sible and Below, 2023). Fungicide application can protect the crop from the biotic stress of fungal diseases (Wise et al., 2019). While some of these practices are used by farmers in Virginia and the Mid-Atlantic region, little research has evaluated their combined effects in corn grain yield in Virginia. Ruffo et al. (2015) found that applying 112 kg N ha<sup>-1</sup> more than the base N recommendation resulted in a 7.9% yield increase. This finding is consistent with Subedi and Ma (2009) and Clay et al. (2009), who examined yield distribution across yield limiting factors in corn in Canada and the Northern Great Plains respectively. In Virginia, the predominant N management strategy is based on determining the appropriate N application rate based on yield goal and applying approximately 1/3 of total N need at planting and 2/3 at the V4-V6 growth stage (Abaye et al., 2023). Supplementing N via multiple in-season N applications called “sidedress” can increase yield when N deficiencies are present (Ransom et al., 2020; White et al., 2023). Previous work has demonstrated increased grain yield with targeted mid-season sidedress N applications at V10 under in Kansas (Sweeney et al., 2018; Sweeney and Ruiz Diaz, 2020).

In addition to N, corn growth and yield are heavily dependent on the season long availability of P and K. Ziadi et al. (2007) found that tissue N and P concentrations declined over the growing season. Moreover, a closer relationship between N and P and grain yield was also confirmed by Schlegel and Havlin (2017) in a long-term corn nutrient study with a positive correlation of P and potassium (K) observed under irrigated conditions. Potassium application is known to increase corn yield, particularly when applied in-season in high-yielding systems or in

fields with deficient soil K. Charbonnier and Ruiz Diaz (2021) demonstrated that in-season application of 56 kg ha<sup>-1</sup> of K increased grain yield by 747 kg ha<sup>-1</sup> above the untreated check under adverse conditions.

In the context of shifting climate patterns, which heighten the challenges associated with crop production, the incidence of diseases and related physiological stress in corn is rising (Yu et al., 2022; Lahlali et al., 2024; EPA, 2023). These biotic stresses can reduce plant health and reduce grain filling resulting in reduced yields. Recent studies from the Northern Great Plains found that the use of fungicides increased corn yield (Wise et al., 2019). Other studies show that biostimulants applications can lead to significant yield improvements, and enhancing nutrient uptake (Farshad et al., 2012; Sible and Below, 2023).

Despite potentially promising research for in-season supplementation of nutrients with N sidedress, P and K supplementation, biostimulants and fungicides for corn in Virginia, they are infrequently used. For them to be part of ACMS, more information is needed on their impact of corn growth and yield. This study aims to evaluate the effectiveness of standard farmer practices and intensive corn management practices in enhancing yields, to determine the yield limiting factors for recommending to farmers under adaptive corn management systems. Additionally, it examines strategies for an ACMS with the hypothesis that adaptive management will achieve more effective results compared to standard management practices.

## **2.2. Materials and Methods**

### **2.2.1. Study site characterization**

Ten studies were conducted during the 2022 and 2023 growing seasons. In 2022, three locations (Blacksburg, New Kent, and Mt Holly) were used, while in 2023, two locations (Mt

Holly, and Suffolk, VA) were used, all featuring both irrigated and non-irrigated sites. The trials evaluated standard Virginia Cooper Extension (VCE, recommended management practices referred to as “standard” and strategies aimed at boosting yield under “intensive” input management, following an addition/omission design (Burati Jr et al., 1992) (Table 2.1). Standard management consisted of selection of hybrids with high yield potential, seeding rate appropriate for the site (65-75,000 seeds ha<sup>-1</sup>), P, K and other nutrients applied per soil test recommendation, and N rate based on yield goal split approximately 1/3 at planting and 2/3 when the corn reached the V4-V6 growth stage (Abaye et al., 2023).

Prior to planting, 15 soil cores were collected from each site to a depth of 15 cm and combined prior to routine soil analysis, pH, and cation exchange capacity (CEC) following the Mehlich-1 weak acid procedure (Table 2.2). These sites varied in their management. The site at New Kent followed a mixed rye and hairy vetch cover crop terminated prior to planting. The Blacksburg site followed a barley cover crop that was similarly terminated. The Mt Holly sites were planted into the previous season’s soybean stubble. While the Suffolk site was planted using strip-tillage following cotton from the previous season. The meteorological data for each site was accessed from Weather Stem station for College of Agriculture and Life Sciences at Virginia Tech (<https://vt-arec.weatherstem.com/data>) (Figure 2.1). Variations in weather patterns were noted during the experimental period. Notable deviations occurred in May to July across the years with Blacksburg, and Mt. Holly in 2022, and Suffolk in 2023 recording less than 100 mm of rainfall. The seasonal rainfall increased again July to August. Regarding temperature, most sites experienced a cool growing season with few high temperatures above 30 C (Figure 2.1).

### **2.2.2. Experiment establishment**

Except at Suffolk where plot sizes were 3.05 m wide (4-rows) and 10.7 m in length; at all other sites plots measured 3.05 m wide (4-rows) and 9.14 m in length. The three sites of Mt Holly, New Kent, and Blacksburg were managed using the no-till practice, while the Tidewater site was subjected to strip-tillage before planting. Soils were mapped as Braddock and Unison silt loam (Fine, mixed, semiactive, mesic Typic Hapludalt) at Blacksburg, as State fine sandy loam (Fine-loamy, mixed, semiactive, thermic Typic Hapludult) at Mt Holly and Suffolk loamy sand at Suffolk (Fine-loamy, siliceous, semiactive, thermic Typic Hapludult). Progeny 9714<sup>®</sup> hybrid (Progeny Ag Products), a 114-day maturity hybrid was used in eight trials, while the two experiments at the Suffolk site (2023), used the 115-day maturity DeKalb 65-20<sup>®</sup> (Bayer Crop Science) hybrid. Planting dates were based on favorable weather and soil conditions, which differed across locations. In 2022, planting occurred on May 5<sup>th</sup> at Blacksburg, April 21<sup>st</sup> at Mt Holly, and May 4<sup>th</sup> at New Kent. In 2023, Suffolk was planted on April 18<sup>th</sup>, and Mt Holly on April 21<sup>st</sup>. This was followed by standard nutrient applications prior to implementation of ACMS management strategies (Table 2.1 and Appendix 2.1).

### **2.2.3. Experimental and treatment design**

Each trial had a total of twelve treatments replicated four times and grouped into two management levels of "standard" and "intensive" management strategies (Table 2.1). All experimental treatments in this study were in addition to the standard check which had only standard inputs at each site based on VCE recommendations. The standard management treatments were standard check (†Standard Check) (representing VCE recommendation), followed by + P and K, + Sidedress N, + Headline, +CoRon, and +Biological as standard management treatments. In contrast, the intensive management included six treatments with the

intensive control (Intensive check) applying all inputs and individual treatments with one input omitted each time to isolate the effects of each input as intensive management treatments (Table 2.1).

#### **2.2.4. Data Collection and Analysis**

Grain yields were determined by harvesting the two center rows from each plot using a small plot combine (Massey-Ferguson 8XP) fitted with Harvestmaster Classic Graingauge. The raw weight data of the plots were standardized at 15.5% moisture content and plot yield was converted to grain yield measured in kilograms per hectare. Data were analyzed by location, irrigation status and management regime using the analysis of variance following a randomized complete block design (RCBD) model in the JMP®, Version 18 (SAS Institute Inc., Cary, NC, 1989-2023). Treatment means were then compared to the appropriate check using Dunnett's test at 90% confidence level. In this way, the standard management check treatment was compared to standard treatments. In contrast intensive check treatment were compared to intensive treatments at a significance level of 90%. Further analysis across different location-year-irrigation combinations was conducted using relative yield (RY). Relative yield was calculated by dividing the yield of each treatment by appropriate check and multiplying by 100.

#### **2.3.0. Results and Discussions**

##### **2.3.1. Effect of treatments and management strategies on grain yield at Blacksburg, New Kent, Mt Holly, and Suffolk Sites.**

Averaged across the sites/years, the impact of irrigation on intensive check treatments resulted in 8.9% more yield compared to non-irrigated. In contrast, irrigating standard management check treatments resulted in a 34% increase in yield compared to non-irrigated. Site

specific results on the impact of irrigation revealed that yield was increased nearly by 38 to 40% at Mt Holly in 2022. At Suffolk in 2023, a 14 and 61% yield increase compared to non-irrigated was observed for intensive and standard management practice treatments, respectively.

When comparing the standard and intensive check treatments, significant differences were detected in 3 of 10 experiments, with two showing a yield increase with intensification under non-irrigated conditions, and one showing yield increase with standard practices under irrigated conditions (Table 2.3). Over all trials, the intensive check yield averaged 5.9% greater than the standard check. Yield of the intensive check was rarely greater than that of standard management check with irrigation. Under non-irrigated conditions adding additional sidedress nitrogen to the standard check resulted in yield increases ranging from 0% to 19%. This indicates that farmers can be able to boost yield with irrigation or supplementation of nitrogen on the standard management practices. Four treatments (+Biological, +P and K, +Headline, and +Sidedress N) demonstrated significant increase on grain yield at 2 out of 10 sites. However, there were also significant yield reductions for individual treatments during the study. For example, at Blacksburg +Sidedress N and +CoRon<sup>®</sup> for standard management resulted in a substantial reduction in grain yield (Table 2.3). At the Mt Holly site in 2023 the treatments with +P and K, +Headline, and +Sidedress N applications produced significantly lower yields than the standard check yield. Despite the significant yield reductions associated with +Headline and +Sidedress N in the irrigated studies at Mt Holly in 2023, these treatments resulted in increased yields at the Suffolk site during the same year, with yields reaching 16,122 kg ha<sup>-1</sup> and 15,545 kg ha<sup>-1</sup> under irrigated and non-irrigated conditions, respectively. Furthermore, while the application of +P and K showed a yield decrease under irrigated conditions at Mt Holly in 2023, the same treatment enhanced yields at Suffolk, achieving 13,659 kg ha<sup>-1</sup> of grain. This finding supports the

importance of site specific management as well as the need to understand yield limiting factors within the context of individual locations. The +Biological application produced a yield increase only once at the Suffolk non-irrigated site, where a yield of 14,238 kg ha<sup>-1</sup> was measured compared to untreated standard check (8,685 kg ha<sup>-1</sup>) (Table 2.3). Lower yields observed with additional N fertilizer application may have resulted from nutrient imbalances negatively impacting grain yield. This aligns with findings from Subedi and Ma (2009), who noted that excessive N rates can disrupt nutrient balance, favoring vegetative growth over reproductive development and ultimately reducing yield.

Under intensive management practices, fewer statistically significant observations were noted. When the P and K were omitted (-P and K) from intensive management, yield declined at the Blacksburg non-irrigated site but increased at Suffolk under irrigated conditions.

Additionally, the omission of biologicals (-Biological) and sidedress N (-Sidedress N) from the intensive check treatments resulted in significant yield increase at Suffolk irrigated and non-irrigated conditions, respectively (Table 2.3). Biological amendments can benefit plants by modifying physiological stress, and enhancing nutrient uptake (Franzen et al., 2019; Sible and Below, 2023; Naseem, H., and Bano, 2014; Franzen et al., 2023a; Franzen et al., 2023b). This explains the yield increase under non-irrigated conditions when the biologicals were added, and yield increase when the biologicals were removed from the irrigated conditions at Suffolk in 2023. The yields at Suffolk rose to 16,226 kg ha<sup>-1</sup> and 16,337 kg ha<sup>-1</sup> when biological and P and K inputs were omitted, respectively, under irrigated conditions. Excluding sidedress N (-Sidedress N) led to a significant yield increase of 14,639 kg ha<sup>-1</sup> in non-irrigated conditions. In contrast, at Blacksburg, omitting P and K caused a significant yield to drop to 7,702 kg ha<sup>-1</sup> in non-irrigated conditions, illustrating their importance in sustaining yield potential. Some sites

had nutrients in the high range based on the pre-plant soil tests (Table 2.2), which suggests limited additional response to applied nutrients (Naseem and Bano, 2014).

#### **2.3.4. Relative yield.**

To evaluate the efficacy of treatments across varied environmental conditions, the data were standardized with the use of relative yield (Table 2.4). When averaged across management practices and compared to their respective controls, the increase in relative yield for the treatments ranged from 71% when sidedress N was omitted from irrigated intensive strategies at the Blacksburg site to 179% when +Sidedress N was incorporated into the standard non-irrigated strategies at Suffolk in 2023. In irrigated scenarios, treatment impacts ranged from 91% (+P and K) to 99% (+Biological) and from 95% (-Sidedress N) to 102% (-Biological) under both standard and intensive management systems. Conversely, under non-irrigated conditions, the overall average treatment impact varied from 102% when foliar N was applied to 119% when extra sidedress N (+Sidedress N) was added and from 95% (-P and K) to 103% (-Biological) for standard and intensive management, respectively (Table 2.4). These findings indicate the importance of appropriately identifying the correct yield limiting factors and the correct management strategies to address them.

#### **2.4. Conclusion**

Across the 10 studies there was inconsistent impact of treatments at all the management levels. The four selected intensive management treatments (biologicals, additional sidedress N, additional P and K, and foliar fungicides) produced inconsistent effects on yield under standard management strategies which varied across locations, reinforcing the need for site-specific management. Under intensive management, the -Biological, and -P and K increased yields under

irrigated conditions, while -Sidedress N increased yields under the non-irrigated conditions indicating that certain expenses in inputs can be avoided without negatively impacting yield and profitability, as well as justifying the correlation of moisture availability on N response.

Irrigation had a paramount effect on yield averaging 8.9% when the intensive management check practices were irrigated and up to 34% when the standard management check practices were irrigated over the non-irrigated treatments (Table 2.3). The results showed a notable difference between the standard farmer practices with those suggested in the advanced corn yield at 3 of 10 experiments. These findings are crucial for developing adaptive corn management strategies that can help farmers to improve farm productivity in the dynamic farming situations.

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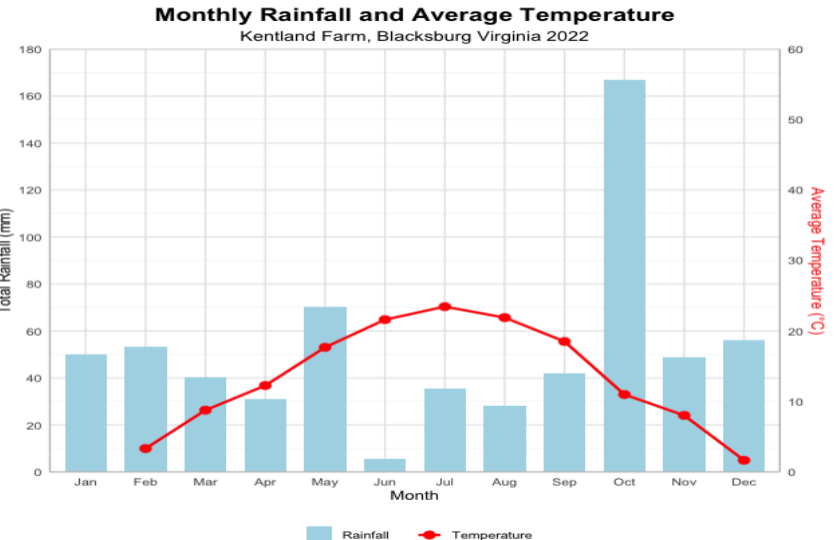
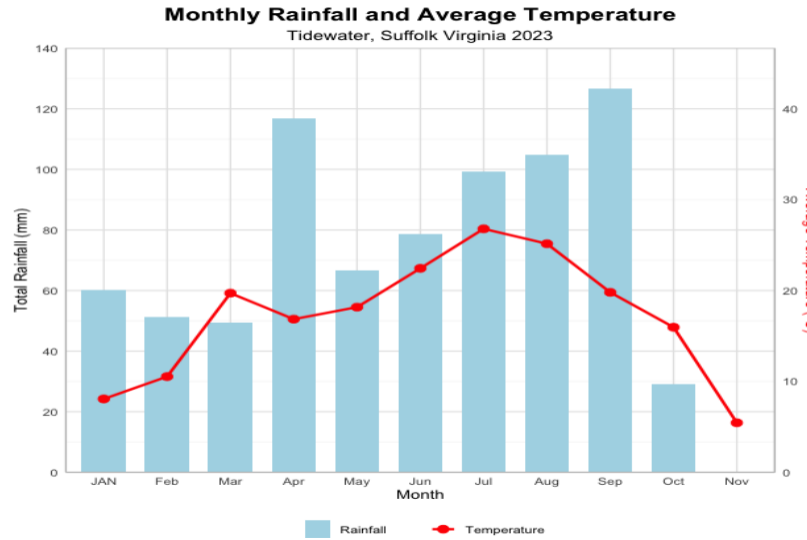
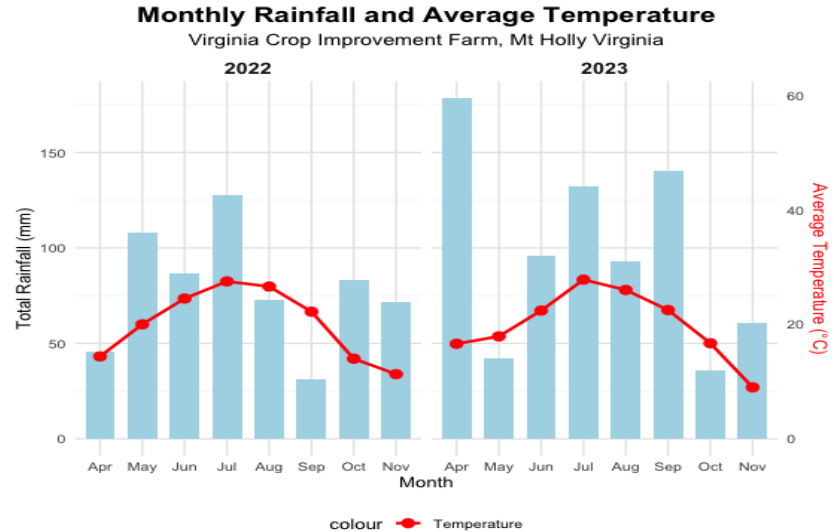
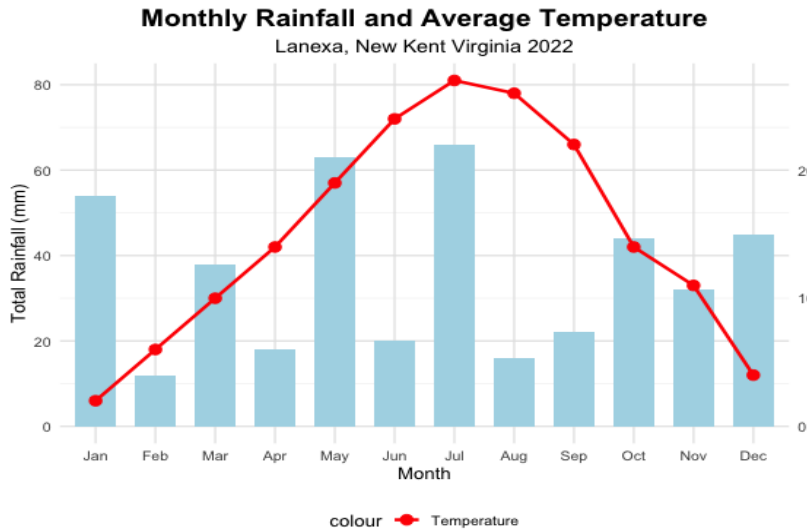
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**Figure 2.1:** Monthly rainfall totals (mm) and average temperatures (°C) recorded during the 2022-2023 field trial periods at New Kent, Mt Holly, Tidewater, and Blacksburg, Virginia.

**Table 2.1: Overview of Omission Treatments in Standard, and Intensive Management Approaches Implemented at All Study Sites 2022-2023**

Treatments	+P and K	+Sidedress N	+CoRon®	+Headline®	+Biological
Application method	.....Sidedressing .....	.....Foliar spraying .....			
Management level	Standard management (One treatment added at a time into standard check)				
†Standard Check	-	-	-	-	-
+P and K	✓	-	-	-	-
+Sidedress N	-	✓	-	-	-
+CoRon®	-	-	✓	-	-
+Headline®	-	-	-	✓	-
+Biological	-	-	-	-	✓
	<b>Intensive management (One treatment taken off at a time from Intensive check)</b>				
‡Intensive check	✓	✓	✓	✓	✓
-P and K	-	✓	✓	✓	✓
-Sidedress N	✓	-	✓	✓	✓
-CoRon®	✓	✓	-	✓	✓
-Headline®	✓	✓	✓	-	✓
-Biological	✓	✓	✓	✓	-

**Symbols:** † = Standard check, ‡ = Intensive check, - = The treatment was omitted. ✓ = Treatment was added.

**Treatment key:** +P and K = additional 56 kg ha<sup>-1</sup> P and K and 11 kg ha<sup>-1</sup> S, +Sidedress = additional sidedress with N 45 kg ha<sup>-1</sup> applied at V6, +CoRon® = Foliar N from a branded nitrogen product CoRon® at 22.5 kg ha<sup>-1</sup> applied at R1 corn stage, +Headline® = Foliar fungicides (headline®) applied at label rate at R1 corn growth stage.

Table 2.2: Soil chemical characteristics of experimental sites at Blacksburg, Mt Holly, New Kent, and Suffolk VA, irrigated and non-irrigated studies in 2022 to 2023.

<b>Location</b>	<b>Year</b>	<b>P</b>	<b>K</b>	<b>Ca</b>	<b>Mg</b>	<b>pH<sup>†</sup></b>	<b>Est CEC<sup>‡</sup></b>
		..... kg ha <sup>-1</sup> .....				1:1	meq/100g
Blacksburg irrigated and non-irrigated	2022	69	289	1283	312	6.1	6.0
Mt Holly Non-irrigated	2022	72	149	1129	301	6.8	3.9
New Kent Irrigated	2022	38	129	731	133	5.5	3.6
New Kent Non-irrigated	2022	61	121	867	169	5.6	4.1
Mt Holly Irrigated	2022	74	164	563	107	5.0	4.3
Mt Holly non-irrigated	2023	58	214	696	173	6.3	3.0
Mt Holly Irrigated	2023	54	161	1031	217	6.3	3.7
Suffolk irrigated and non-irrigated	2023	56	82	665	74	6.6	1.9

<sup>‡</sup>Cation exchange capacity

<sup>†</sup>Soil pH measure from the 1:1 water to soil

Table 2.3: Effect of intensive management input and omission on corn grain yield, Blacksburg, New Kent, and Mt. Holly, 2022; and Mt. Holly and Tidewater, 2023.

Year	-----2022-----						-----2023-----			
Location	Blacksburg		New Kent		Mt Holly		Mt Holly		Suffolk	
Irrigation status	irrigated	non-irrigated	irrigated	non-irrigated	irrigated	non-irrigated	irrigated	non-irrigated	irrigated	non-irrigated
Standard management compared to the †Standard Check										
Management level	----- Grain yield, kg ha <sup>-1</sup> -----									
+Biological	10354	11111	19188	15233	13201	9750	15472	11527	15454	14238 *
+CoRon®	8755 *	7900	17834	16902	14194	9441	15455	13790	14262	10109
+Headline®	10113	7936	18445	16263	13847	9666	14300 *	11786	16122 *	11692
+P and K	9374	9729	16317	18022	12696	9845	14144 *	12693	14651	13659 *
+Sidedress N	8233 *	9166	18923	16855	13464	10285	14718 *	13245	14204	15545 *
†Standard Check	11195	8149	18202	15751	13789	9832	16624	14529	13962	8685
Intensive management Compared to the ‡Intensive check										
Management level	----- Grain yield, kg ha <sup>-1</sup> -----									
-Biological	9207	11513	18770	16086	13665	10145	13411	12706	16226 *	12810
-CoRon®	10768	11240	17963	16675	13542	8584	13266	12711	15531	12839
-Headline®	10115	9161	18212	16398	12826	10345	12800	13093	15522	11610
-P and K	9461	7702 *	17744	17287	12488	9131	13182	13311	16337 *	12071
-Sidedress N	7337	9031	18743	15859	12570	9711	13186	13569	16023	14639 *
‡Intensive check	10286	10944	18138	18743	13029	9437	13373	13179	14645	12810
Management level										
Intensive check	10286	10944	18138	18743	13029	9437	13373	13179	14645	12810
Standard check	11195	8149	18202	15751	13789	9832	16624	14529	13962	8685
P-value	0.608	0.051	0.944	0.004	0.343	0.694	0.041	0.233	0.334	0.357
Irrigation impact, %										
Intensive check	-6%		-3%		38%		1.5%		14%	
Standard check	37%		16%		40%		14%		61%	

Dunnett's test was employed for mean differences from the check, with significance determined at  $P \leq 0.1$ . Treatment differences followed by \* are statistically significant at  $p < 0.1$ . Average impact of irrigation in intensive = 8.9. Average impact of irrigation in standard: 34%

Table 2.4: Relative yield of standard and intensive management practices Blacksburg, New Kent, and Mt. Holly, 2022; and Mt. Holly and Tidewater, 2023.

Irrigation	-----Irrigated-----						-----Non-irrigated-----					
	-----2022-----			-----2023-----			-----2022-----			-----2023-----		
	Year	Site	Year	Site	Year	Site	Year	Site	Year	Site	Year	Site
	Blacksburg	New Kent	Mt Holly	Mt Holly	Tidewater	Avg	Blacksburg	New Kent	Mt Holly	Mt Holly	Tidewater	Avg
<b>Standard management compared to the †Standard Check, %</b>												
+Biological	92	105	96	93	104	98	136	97	99	79	164	115
+CoRon®	78	98	103	93	102	95	97	107	96	95	116	102
+Headline®	90	101	100	86	115	99	97	103	98	81	135	103
+P and K	84	90	92	85	105	91	119	114	100	87	157	116
+Sidedress N	74	104	98	89	102	93	112	107	105	91	179	119
Mean						95						111
<b>Intensive management compared to ‡Intensive check, %</b>												
-Biological	90	98	105	100	111	101	105	86	108	96	120	103
-CoRon®	105	94	104	99	106	102	103	89	91	96	120	100
-Headline®	98	95	98	96	106	99	84	87	110	99	108	98
-P and K	92	93	96	99	112	98	70	92	97	101	113	95
-Sidedress N	71	98	96	99	109	95	83	85	103	103	137	102
Mean						99						100

Comparison of the †standard check with "standard management," and ‡intensive check with "intensive management". Mean relative impact of treatments and their check were calculated by dividing the treatment mean by the highest mean multiplied by 100%. Acronyms: Avg=Average.

## Appendix 2

### Appendix A2.1: Fertilizer Rate Totals by Treatments for Standard and Intensive Management (2022-2023)

Site/year	Blacksburg VA				Mt Holly 2022-2023						New Kent 2022						
	2022				2022 Season			Irrigated 2023			Non irrigated 2023			Both irrigated and non			
Treatments	N	P	K	S	N	P	K	N	P	K	N	P	K	N	P	K	S
	.....Kg ha <sup>-1</sup> .....																
†Standard Check	211	109	109	18	211	78	39	211	67	111	211	44	67	185	44	89	0
+P and K	211	165	165	29	211	133	94	211	122	167	211	100	122	185	100	144	11
+Sidedress N	256	109	109	18	256	78	39	256	67	111	256	44	67	230	44	89	0
+CoRon®	233	109	109	18	233	78	39	233	67	111	233	44	67	206	44	89	0
+Headline®	211	109	109	18	311	78	39	245	67	111	272	44	67	185	44	89	0
+Biological	211	109	109	18	211	78	39	211	67	111	211	44	67	185	44	89	0
‡Intensive check	278	165	165	29	278	133	94	278	122	167	278	100	122	253	100	144	11
-P and K	278	109	109	18	278	78	39	278	67	111	278	44	67	253	44	89	0
-Sidedress N	233	165	165	31	233	133	94	233	122	167	233	100	122	208	100	144	11
-CoRon®	256	165	165	29	256	133	94	256	122	167	256	100	122	230	100	144	11
-Headline®	278	165	165	29	278	133	94	278	122	167	278	100	122	253	100	144	11
-Biological	278	165	165	29	278	133	94	278	122	167	278	100	122	253	100	144	11

### **3.0: Optimum management strategies for corn when utilizing subsurface drip irrigation in the Mid-Atlantic United States**

#### **Abstract**

With less than 5% of Virginia's arable land irrigated, maintaining sustainable crop yields will be challenging in the face of climate change and unpredictable rainfall events. Subsurface drip irrigation (SDI) offers a promising irrigation alternative compared to more traditional overhead systems given Virginia's small, irregularly-shaped fields. A three-year study evaluated optimal SDI strategies and the interaction between irrigation, corn seeding rates, and nitrogen (N) application rates. A split-split-plot design was used to evaluate six SDI strategies (non-irrigated (control)), 0.91 m dripline spacing, 1.82 m dripline spacing, 0.91 m + volumetric water content (VWC) sensor, 0.91 m + fertigation, 1.82 m + fertigation (2022 only), and 0.91 m + Pivot Bio® (2023 and 2024)), four seeding rates (59,280 to 103,740 plants ha<sup>-1</sup>), and four N rates (133 to 333 kg N ha<sup>-1</sup>). Data analysis was performed in R Studio version 4.4.1. Irrigation, N application rate, and seeding rate significantly influenced grain yield, and there was a significant interaction between irrigation and N rates all the years. Yearly irrigation impact on grain yield was 102%, 13%, and 51% over non-irrigated in 2022, 2023, and 2024, respectively. Averaged over three years, the 0.91 m dripline resulted in the highest increase in revenue (\$985 ha<sup>-1</sup>) compared to non-irrigated corn production systems. These findings highlight SDI's effectiveness towards increasing yield and profitability of corn, lowering production risks, in Virginia and the mid-Atlantic region.

## Core ideas

- Yearly impact of irrigation on grain yield increase was 102%, 13%, and 51% compared to no irrigation.
- The 0.91-meter dripline spacing yielded the highest gross revenue (\$985 ha<sup>-1</sup>) over non-irrigated.
- The 0.91 dripline automated with a VWC sensor added \$885 ha<sup>-1</sup> in revenue over non-irrigated.
- Grain yield increased with nitrogen rates at all irrigation levels, except in non-irrigated.
- The highest rate of yield increase was attained at 88,920 plants ha<sup>-1</sup> and 267 kg ha<sup>-1</sup> nitrogen.

### 3.1. Introduction

Corn (*Zea mays L.*) is the most widely grown grain crop in the world and is used for food, feed, fuel, and industrial uses (Larson et al., 2010; FAO, 2020). In the US, corn is grown on approximately 36.7 million hectares (USDA-NASS, 2024). Virginia averaged 186,234 hectares of corn in 2024 with an average grain yield of 10,042 kg ha<sup>-1</sup>, which was 892 kg ha<sup>-1</sup> lower than the national average (10,934 kg ha<sup>-1</sup>) (USDA-NASS, 2024). Corn growth and yield are affected by the availability of nutrients, water, plant population, and environmental stresses (Eck, 1984; Ruffo et al., 2015; Ruffo, 2024, Clay et al., 2009; Subedi and Ma, 2009). Although irrigation is one of the strategies to advance corn yield, it has not been adopted extensively in Virginia; with < 5% of the total corn area irrigated (USDA-NASS, 2024).

Globally there are an estimated 255.2 million hectares of irrigated agricultural lands of whom 53.1 million were reported in the United States in 2023 census of irrigation (USDA-NASS, 2024) despite supplying over 40% of the world's food (Misra, 2014; Yihdego et al., 2019). NASA's recent drought forecast indicated that all food-producing regions worldwide experience a cumulative one month of drought annually, indicating the need for drought mitigation strategies (King et al., 2024). In the U.S., irrigated corn occupies 17% of total irrigated land, a figure expected to rise due to climate change, and the push for higher yields. Additionally, the water demand by the current enterprises will increase by over 80% and over 230 million people will have shortage of water (Flörke et al., 2018; Kukul and Irmak, 2019; King et al., 2024). Agriculture withdraws large quantities of water and is in direct competition for water resources with suburban and urban uses. Thus, any irrigation system and management must be highly efficient and provide enough water to optimize crop yields. However, Virginia faces limitations in adopting irrigation. Virginia Department of Environmental Quality (VA-

DEQ) regulates water withdrawals through permits under the Virginia Water Protection (VWP) program and imposes thresholds of water use. For instance, agricultural operations that withdrawals water exceeding 1,135,624 liters per month from nontidal waters require specific permits (VA-DEQ, 2024). These factors, alongside limitations of traditional irrigation methods in non-uniform field shapes and small field sizes, complicate irrigation adoption. Addressing these challenges requires selecting a water-efficient, cost-effective irrigation system that can supplement seasonal precipitation. Additionally, the system must be flexible to irrigate all fields irrespective of shapes and be flexible for adaptive irrigation in response to droughts.

In Virginia, commonly used irrigation systems include center pivot overhead systems, which have specific limitations that can impact its efficiency. These systems are effective for covering large open areas, but significant water loss due to evaporation and runoff can occur, especially during hot summer months (Yonts et al., 2000; Cahn and Hutmacher, 2024). Additionally, this system requires a substantial initial investment and can be constrained by the shape and size of the fields (Dong et al., 2020; Cahn and Hutmacher, 2024). In contrast, subsurface drip irrigation (SDI) offers a more efficient solution by delivering water directly to the root zone, minimizing evaporation, and maximizing water use efficiency. The SDI system can be tailored to various field shapes and sizes, providing a viable alternative for Virginia farmers. Research from Nebraska shows SDI can match or exceed crop yields of overhead center pivot irrigation systems (Lamm et al., 2009). Through this system, water and nutrients can be directed to plant roots through fertigation reducing water and nutrient losses (Ward and Pulido-Velazquez, 2008; Cahn and Hutmacher, 2024). With proper maintenance, a subsurface drip irrigation system can last 20 to 25 years (Lamm and Trooien, 2003; Lamm et al., 2009).

Key variables such as seeding rates, nutrient application rates, dripline spacings, crop type, soil type, and evaporation demands must all be considered when using an SDI system (Lamm et al., 2000). Extensive research has shown that these factors influence the size and placement of drip lines, which are influenced by crop row spacing (Lamm et al., 2000; Eisenhauer et al., 2021; Cahn and Hutmacher, 2024). Drip line spacings, and depth of placement affects crops moisture supply, which also impact crop yield (Enciso, 2004; Lamm et al., 2000; Eisenhauer et al., 2021; Bayabil et al., 2023).

The relationship of corn seeding rates, N application, and irrigation is crucial for maximizing yields. Higher plant populations may directly lead to more ears per hectare and grain yield but may intensify competition for above-ground and below-ground resources, as elevated canopy evapotranspiration heightens water demands while roots compete for moisture and nutrients (Al-Kaisi and Yin, 2003; Licht et al., 2019; Bernhard and Below, 2020; Bayabil et al., 2023). High populations may require higher N rates to support optimum growth (Cheng et al., 2024). Conversely, lower populations may enhance nutrient uptake and moisture availability per plant, especially under fertigation (Csöff, 2018; Lamm et al., 2004). The optimal seeding rates for corn falls in the range of 61,750 to 81,510 plants per hectare (Abaye et al., 2023). Corn grain yields can be increased substantially by combining optimal seeding rates, effective N management practices that reduce nutrient losses, and targeted irrigation, (Cheng et al., 2024).

Nitrogen is crucial for corn growth, development, and yield, due to its direct involvement in the biochemical and physiological such as chlorophyll production and protein assimilation. Managing N is challenging due to the many loss pathways in the N cycle and mobility in the soil environment. In Virginia's humid climate, heavy summer and fall rains may lead to potential N losses via leaching or denitrification. Conversely, drought conditions can occur after fertilizer

application, reducing nutrient availability (Reiter et al., 2018). Subsurface irrigation may help to alleviate these concerns by utilizing fertigation to apply N directly in the root zone for more efficient uptake (Aubert et al., 2016; Paramesha et al., 2022; Zhang et al., 2024). Dixon and Liu (2022) reported that corn under fertigation achieved a 15% yield increase compared to conventional fertilization.

As production costs rise and sustainable practices gain emphasis, growers seek to reduce N application rates. Biological N fixation (BNF) offers a viable alternative to synthetic fertilizer N (Franzen et al., 2023). The BNF formulation currently available are a promise to sustainable future of agriculture that can reduce the exogenous N footprints in the environment. Only a small percentage of land plants form symbiotic relationships with microorganism capable of fixing atmospheric N, however crops such as corn and cotton depend on soil and/or applied N fertilizers to meet their respective demand for N. Currently, several branded microbial products are promoted to fix N up to 45 kg ha<sup>-1</sup>, such as Pivot Bio's ProveN40™ (Pivot Bio, Inc. Berkley, CA). However, the efficacy of BNF is influenced by many factors including soil texture, moisture, and microbial dynamics; requiring performance of products to be evaluated regionally (Yang et al., 2022). Recent research in the North Great Plains showed a highly variable response, further encouraging regional evaluation (Franzen et al., 2023). Nonetheless, little is known is Virginia regarding their performance in conjunction with an SDI system.

The objectives of the study were to: 1) to quantify the impact of SDI system strategies on corn grain yield in Virginia and 2) evaluate how corn seeding rates and N applications rates effect corn grain yield with and without SDI.

## **3.2. Materials and Methods**

### **3.2.1. Study site characteristics and system design:**

The study was conducted over three growing seasons (2022 - 2024) at the Tidewater Agricultural Research and Extension Center (TAREC) in Suffolk, Virginia (36° 39' 48.48" N, 76° 44' 10.56" W). The SDI system was installed on 1.4 hectares in 2017 and was designed for deficit/supplemental irrigation. The system has a total of eighteen irrigation zones and driplines were laid to a depth of 25 cm and spaced 0.91 m apart. Every other 0.91 m dripline can be turned off to change the dripline spacing to 1.82 m. Driplines were donated by Toro® Micro-irrigation (El Cajon, California) with emitters spaced 40.6 cm apart providing a flow rate of 0.6 liters per hour. Water for the system was sourced from a pond and water was filtered through sand filters before reaching the driplines. Each irrigation zone was 94 m long, and 7.3 m wide. The soil type was predominantly Eunola fine loamy sand soil (78.8%), and the remaining was Kenansville loamy sand (21.2%) on a gently sloping site managed with strip-till, and the rotation was cotton-corn-corn-corn rotation. The soils were sampled pre-plant and analyzed using Mehlich-I for extractable nutrients, pH, and CEC, and soil test results are included in Table 3.1.

### **3.2.2. Irrigation strategies**

The study was designed as a split-split plot, with six irrigation strategies as the whole plot treatments, four seeding rates as the sub-plot treatments, and four N application rates as the sub-sub plot treatments for a total of 96 treatment combinations with three replications. The irrigation treatments were no irrigation, 0.91 m dripline spacing, 1.82 m dripline spacing, 0.91 m dripline spacing with fertigation, 1.82 m dripline spacing with fertigation (2022 only), 0.91 m dripline spacing with irrigation scheduled using soil volumetric water content sensor (VWC), and a 0.91 meter dripline with Pivot Bio® (only in 2023 and 2024). Irrigation scheduling was performed

using the checkbook method except where VWC sensors were implemented (Gu et al., 2020). ProveN40™ (Pivot Bio, Inc. Berkley, CA) a biological N product application replaced 45kg ha<sup>-1</sup> of the standard N rates in the treatments where it was applied. In the sensor-based irrigation system, VWC sensors (TEROS 21™ VWC sensors) were used to enable remote monitoring and data collection of soil moisture content at 15-minute intervals. Three sensors were placed in each of the three replications in the sensor-based irrigation treatment at a depth of 0.91 m and collected data at an interval of 10.2 cm depth. These sensors measure the volumetric water content (VWC) of the soil (Figure 3.1). Irrigation was triggered when VWC fell below 12% which is below the field capacity of 14% for the Eunola fine sandy loam measured by pressure plate apparatus. By scheduling irrigation based on VWC sensor data, the system ensures timely irrigation, preventing both over-watering and water stress. (Cheng et al., 2024).

### **3.2.3. Seeding rate strategies**

The sub-plot treatments were four seeding rates of 59,280, 74,100, 88,920, and 103,740 plants ha<sup>-1</sup> were planted within each irrigation zone. These rates encompassed the typical range of seeding rates utilized in corn production in Virginia for high-yielding and low-yielding areas, environment (Abaye et al., 2023). The trial was planted using a small plot research planter on April 28<sup>th</sup>, 20<sup>th</sup>, and 16<sup>th</sup> in 2022, 2023 and 2024, respectively. Due to a mistake in 2024 at the initial planting of the test, irrigation zones receiving Pivot Bio were planted without the biological product and then killed after emergence and replanted 14 days after the previous seeding with the in-furrow treatment. After complete emergence, stand counts were conducted by counting the number of seedlings on an area of 3.05 meters long in two rows and taking the average for each plot for two replications of each treatment (data not shown).

### 3.2.4. Nitrogen application rate strategies

The sub-sub plot treatments used N application rates of 133, 200, 267, and 333 kg N ha<sup>-1</sup>. At planting, 45 kg N ha<sup>-1</sup> was applied in a 5x5 starter band, and the remaining N was applied at V5-V7. The N sources used were 32% urea ammonium nitrate solution (UAN) with ammonium thiosulfate (12-0-026S, ATS) subsurface banded 20 cm to the side of the row and 10 cm deep in 2022 and 2023; and granular urea (46-0-0) and ammonium sulfate (21-0-0-24S, AMS) treated with a urease inhibitor were used in 2024. In the fertigated treatments, 89 kg N ha<sup>-1</sup> was applied via the SDI system over the period of eight weeks and the remaining N was applied the same timing as sidedress N applications, except for the 133 kg N ha<sup>-1</sup> treatment which did not receive sidedress N application. For the Pivot Bio® treatments, N rates were reduced by 45 kg N ha<sup>-1</sup> to account for the 45 kg N ha<sup>-1</sup> claimed to be supplied by the in-furrow formulation.

### 3.2.5. Data collection

Seasonal moisture data were collected using VWC sensor TEROS 21™ sensors (Figures 3.1 and 3.2), while weather data were obtained from the Virginia Peanut-Cotton [InfoNet](#) for detailed seasonal precipitation and temperatures (Figures 3.3-a, 3.3-b). The irrigation controller uploaded irrigation logs to a Netafim server in 2022; in 2023 the server was shut down without notice and irrigation logs were lost; in 2024 the irrigation events were manually logged (Figure 3.2). These were then converted to millimeters units by multiplying the final figure to 25.4 (Waller et al., 2016).

#### Equation 3.1:

$$\text{Irrigation (acre-inches)} = (\text{Total gallons}) / (\text{Zone area (310 x 24 (reps 3))} / \text{area of an acre (43,560)}) \times \text{conversion factor for gallons to acre-inches (27,154)}.$$

Two center rows of the four rows wide plots 7.6 m in length were harvested for grain yield using a Zurn 150 small plot combined equipped with a Harvest master Classic Grain gauge (Zurn Harvesting GmbH & Co. KG, Germany.) Grain samples were collected at harvest and analyzed using a Dicky John 2100 for test weight and moisture content. The grain yield for each plot was adjusted to 15.5% moisture content.

### **3.2.6. Statistical Analysis**

The data were analyzed using R studio version 4.4.1 while the graphical presentations were done in the JMP®, Version 18 (SAS Institute Inc., Cary, NC, 1989-2023). Nitrogen rate by irrigation interactions were analyzed linear regression analysis using Sigma Plot 15.0 (SYSTAT Software Inc., 2023). Data were analyzed separately by site year (2022-2024) as years differed in the initial combined analysis. The model ssp. plot (block, pplot, splot, ssplot, Y) was employed in R studio version 4.4. 1 (de Mendiburu and de Mendiburu, 2019) in library Agricola. The Tukey HSD test was applied for mean separation to analyze differences among irrigation strategies, employing an alpha level of 0.1.

A three-year (2022 to 2022) average price of corn grain received of \$0.24 kg<sup>-1</sup> from USDA-NASS, accessed in December 2024 was considered in the calculation of the economic viability of the irrigation investments. The difference from non-irrigated was calculated and the results were multiplied by the price to get the gross financial return between the non-irrigated and other irrigation strategies.

To standardize grain yield across years, relative yield was calculated for a combined analysis, (dividing the plot yield in each year by the greatest mean treatment yield and multiplying by 100) allowing for a comparison of treatments over the three-year period. In this analysis, irrigation was considered as whole plot factor (fixed), while, seeding rates, and nitrogen

rate strategies were considered sub and sub-sub plots respectively (fixed), and replicates were considered random effects:

$$\gamma_{ijkl} = \mu + \alpha_i + \beta_j + \gamma_k + (\alpha\beta)_{ij} + (\alpha\gamma)_{ik} + (\beta\gamma)_{jk} + \delta_l + \epsilon_{ijkl}$$

Where  $\gamma_{ijkl}$  is the observed response variable,  $\alpha_i$  is the main effect of irrigation,  $\beta_j$  is the main effect of seeding rates,  $\gamma_k$  is the main effect of N rates while the rest represents the possible interaction between model components.

### **3.3.0. Results and Discussion**

#### **3.3.1. Weather, and irrigation scheduling**

The seasonal weather patterns are presented in Figure 3.3-a, illustrating daily maximums of rainfall, maximum temperatures, minimum and the average daily temperatures at the experimental site through the season. These were compared to the 30-year averages on the same site (Figure 3.3-b). Over the course of the three observed years, variability in temperature and precipitation levels were noted, which may have impacted corn growth and response to treatments (Figures 3.3-a). Precipitation varied greatly with 2022 recording maximum daily rainfall < 10 mm from May 1 through July 3<sup>rd</sup> and 3 weeks (July 4<sup>th</sup> to 24<sup>th</sup>) of no rainfall. This was similar to 2023 growing season which was characterized by early drought (May 15<sup>th</sup> through June 12<sup>th</sup>) with less than 5 mm of rainfall, and a same trend observed on June 26<sup>th</sup> to July 17<sup>th</sup>, although these were comparable to the long-term average precipitation. Each season had at least two weeks of drought, although these happened at different parts of growing season. Notable conditions were high rainfall in July 2023 and 2024 of up to 70mm of daily rainfall, after consistent dry period which coincided with N sidedressing. In 2022, there was several rainfall peaks each above 30mm of rainfall, similar to 2023 with 3 peaks one of them reaching 60mm of

rainfall between July 24 and August 7<sup>th</sup>. Similarly, the month of June to July, pivotal for peak growth and reproductive stages, consistently exhibited dry conditions in all three years with < 10mm of daily maximum rainfall and several days of temperatures >30 degrees Celsius, which were hotter than the long-term average. Timely irrigation during the V4/V5 growth stages and effective N management likely mitigated early drought stress, facilitating a greater response to irrigation strategies in 2022 and 2024. Presented in Figure 3.2 are the totals of irrigation and precipitation. In 2022, the irrigated treatments received almost double the amounts of seasonal moisture compared to the non-irrigated. For example, irrigation with precipitation resulted in an aggregate water supply of 420 mm for the 0.91 m dripline, surpassing the 268 mm supplied to the non-irrigated treatments by 152 mm in 2022 (Figure 3.2). In 2023, the server receiving irrigation quantities from the controller was shut down without notice and all 2023 irrigation data was lost. In 2024, a significant dry period was noted between June and July, evidenced by wilting and desiccation of lower leaves in the non-irrigated plants (Figure A3.2 and A3.5). However, a marked increase in precipitation from the end of July through August potentially enhanced growth conditions during this latter part of the season, explaining the higher yields obtained from the Pivot Bio® treatment which was planted two weeks later in the season.

### **3.3.2. Effect of irrigation, seeding rates, and nitrogen rate strategies on grain yield and quality**

#### **3.3.2.1. Irrigation.**

Grain yield was significantly affected by irrigation strategies across all years and irrigation and N rate interactions were also significant across the three years (Figures 3.4 to 3.6, Table 3.2). The interaction between irrigation and seeding rates was only significant in 2022 (Table 3.3). Across all three years, yield gains were observed with irrigation, regardless of the

application strategy. In 2022, the highest grain yield (13,248 kg ha<sup>-1</sup>) was achieved with a 0.91 m dripline equipped with VWC sensors, followed by a 0.91 m dripline with fertigation (12,856 kg ha<sup>-1</sup>). Non-irrigated treatments produced the lowest yield (6,054 kg ha<sup>-1</sup>), with irrigation strategies increasing grain yields on average 5,320 kg ha<sup>-1</sup> and as much as 7,194 kg ha<sup>-1</sup> (0.91 m dripline with VWC sensor) compared to non-irrigated conditions, leading to gross financial benefits of \$1,277 to \$1,727 ha<sup>-1</sup> at \$0.24 kg<sup>-1</sup> of corn grain. In 2023, similar trends were observed, with the 0.91 m dripline producing the highest yield (11,152 kg ha<sup>-1</sup>), followed by the 0.91 m dripline with Pivot Bio's ProveN40™, yielding 1,945 kg ha<sup>-1</sup> more than the non-irrigated control, leading to the net economic impact of \$467. Similarly, in 2024, the 0.91 m dripline again showed the highest yield (11,131 kg ha<sup>-1</sup>), with the ProveN40 treatment achieving 10,872 kg ha<sup>-1</sup>. Both treatments produced 4,314 and 4,054 kg ha<sup>-1</sup> more grain than the non-irrigated control, resulting in net financial gains of \$1,035 and \$973 ha<sup>-1</sup>, respectively.

Averaged across the three years, the 0.91 m dripline produced the highest financial return at \$985, followed by the 0.91 m dripline with VWC sensor at \$886 over the non-irrigated control. Based on these findings, the estimated average cost of installation of the system (\$6,175 ha<sup>-1</sup>), and its maintenance, the farmer may need only 6 to 9 years to pay off system costs and improve profits for the next 15 years.

Corn's yield potential relies on a stress-free grain fill period, with the source-sink relationship being crucial for maximum grain filling capacity and overall yield (Seebauer et al., 2010). These findings are supported by Powell and Wright (1993) who reported a yield advancement on narrower dripline that was associated with higher water availability under the Suffolk growing conditions. The higher grain yield in sensor controlled strategies is likely due to targeted supply of nutrients and moisture to meet the evaporative demands, as reported by Csöff

(2018) and Lamm et al. (2001), also aligning with Lamm et al. (1997) on the optimum dripline spacing. These findings dictate that targeted supply of water at critical periods adaptively enhance grain yield in the droughty soils of Eastern Virginia.

### **3.3.2.2. Seeding rate strategies**

Significant differences in grain yield due to seeding rates were observed across irrigation strategies and N application rates each year of the study. The interaction between seeding and irrigation rates were significant only in 2022 (Table 3.3). The results showed that grain yield increased with increasing seed rate (59,280 to 74,100) with the greatest yield attained at the 88,920 seeding rate in 2022 and 2023, and at a 74,100 seeding rate in 2024 (Table 3.4). The relationship between seeding rates and corn yield is a critical factor influencing corn productivity (Ruffo, 2024). Higher seeding densities/high stands can lead to increased grain yield under optimal conditions (Ruffo, 2024). However, under stressed conditions, the reverse is true, which explains the significant interactions of irrigation and seeding rates in a drier year of 2022 (Table 3.3). Lower seeding rates allow corn plants to develop more fully due to reduced competition for resources, but they can result in fewer plants and ears per area (Farnham, 2001). In contrast, higher seeding rates increase plant density, leading to competition for water and nutrients, which can hinder individual plant growth, yet enhance overall yield due to more plants producing ears under non resource limited environment (Farnham, 2001; Fiorucci and Fankhauser, 2017). This competition is particularly intense in drought-prone sandy soils, where moisture and CEC is lower, helping to explain the greatest yield increase up to at 88,920 plants per hectare and a declining response to higher seeding rates (103,920 plants per hectare) in 2022 (Tables 3.3, and 3.4). These findings are better understood through the interaction between seeding rates and irrigation observed in 2022. At a higher seeding rate of 103,740 seeds per hectare, the

combination of closer dripline spacing (0.91 m), and irrigation scheduled using VWC sensors applied greater water volumes (Figure 2). This approach resulted in the highest yield of 14,003 kg ha<sup>-1</sup> in 2022 (Table 3.3). This was largely because greater resource optimization (seeding rates, and irrigation) reduced drought stress experienced from July 4<sup>th</sup> to July 24<sup>th</sup>, 2022 (Figure 3.3-a). Thus, understanding these dynamics aids farmers in making informed decisions to balance planting density and irrigation dripline spacing to achieve sustainable yields under variable weather conditions.

### **3.3.2.3. Effect of nitrogen rates strategies**

Nitrogen rates significantly affected on grain yields each year of the study (Table 3.4). Additionally, the N and irrigation strategies interacted and influenced grain yield across years (Figures 3.4 to 3.6). Grain yield increased with increasing rates of nitrogen applied reaching the highest yield at the highest rates (333 kg N ha<sup>-1</sup>) in all the three years. When N rates were compared across irrigation strategies the lowest application rate of 133 kg N ha<sup>-1</sup>, produced increased grain yields above non-irrigated ranging from 1,650 to 2,323 kg ha<sup>-1</sup> in 2022, 1,463 to 2,334 kg ha<sup>-1</sup> in 2023, and 1,459 to 2,231 (Tables 3.4). The interaction between nitrogen rates and irrigation significantly influenced grain yield across the three years, despite variations in weather and agronomic conditions (Figures 3.3a to 3.3b). Our results demonstrate that increased N application under irrigated conditions enhanced grain yield compared to non-irrigated, aligning with findings by Fageria and Baligar (2005), who reported that N availability supports optimal crop development when water is not limiting. Similarly, Bai et al. (2024) highlighted the synergistic effects of N and water in maximizing crop yields, while Derby et al. (2005) emphasized the role of N in improving water-use efficiency under irrigated scenarios in North Great Plains. These parallels underscore the critical relationship between N application and

irrigation in achieving higher grain yields. This interaction was primarily driven by the consistent increase in grain yield across all irrigation strategies as N rates increased, except under non-irrigated conditions.

However, not all irrigation strategies had significant responses across N application rates during the 3-year study period. Regression analyses found the response of grain yield to N application rates across different irrigation strategies during the 3-year study period. In 2022 and 2023, four irrigation strategies demonstrated significant relationships between N application rates and grain yield. In 2024, only three irrigation strategies exhibited significant regression models. Notably, for non-irrigated plots, significant regression models were not observed in two of the three years, indicating limited responsiveness of grain yield to N application rates under non-irrigated conditions. These findings are illustrated in Figures 3.4 to 3.6 and summarized in Tables 3.3 and 3.5.

The 1.82 m dripline spacing responded similarly during the study with a significant regression interaction only occurring in 2022. Responses to N application rates in irrigated treatments followed a linear response in 10 of 15 observations. An interesting finding is that the biological amendment (ProveN40<sup>®</sup>) strategy showed a significant positive interaction between N application rate for both years the product was evaluated. It was the only treatment combination that demonstrated a significant quadratic regression relationship in both years of the study indicating that increases in grain yield diminished with increasing N application rates. These findings align with the relationships described by Fageria and Baligar (2005), emphasizing the critical role of N in plant growth and development (Figures 3.4 to 3.6 and Table 3.5). The higher response in grain yield using 0.91 m drip spacing with VWC and high rates of N 333 kg N ha<sup>-1</sup> in 2022 is due to the targeted application of irrigation water before the crop suffered stress.

Moreover, the same irrigation strategy showed higher yield at the lower N rates ( $133 \text{ kg N ha}^{-1}$ ) which shows promise towards advancing yield of corn with adaptive irrigation and targeted nutrient application.

### **3.4. Summary and Conclusions**

This study evaluated the effect of irrigation strategies, N application rates and seeding rates on corn grain yield across three growing seasons (2022-2024). Irrigating corn on coastal plain soils of the Mid-Atlantic region with SDI is feasible and can be sustainable economically. Over the three years of the study, the 0.91 m dripline, the 0.91m dripline in combination with VWC sensors and the 0.91 m dripline in combination with fertigation averaged the greatest gross economic benefit of \$985, \$886, and \$816  $\text{ha}^{-1}$  over non-irrigated respectively, alongside a return on investment between 6, 7, and 8 years after the initial investment cost of \$6,175  $\text{ha}^{-1}$ . Averaged over years, irrigation resulted in 102%, 13% and 51% increases in grain yield in 2022, 2023, and 2024 respectively. Nitrogen application rates as well as their interactions with irrigation highlighted the necessity of sufficient moisture for optimal nutrient uptake on crop yield. This study demonstrates that targeted irrigation and N management can maximize corn yield. The findings will support the implementation of SDI irrigation management and help identify the optimum seeding rates and N application rates for the Mid-Atlantic region in the SDI system.

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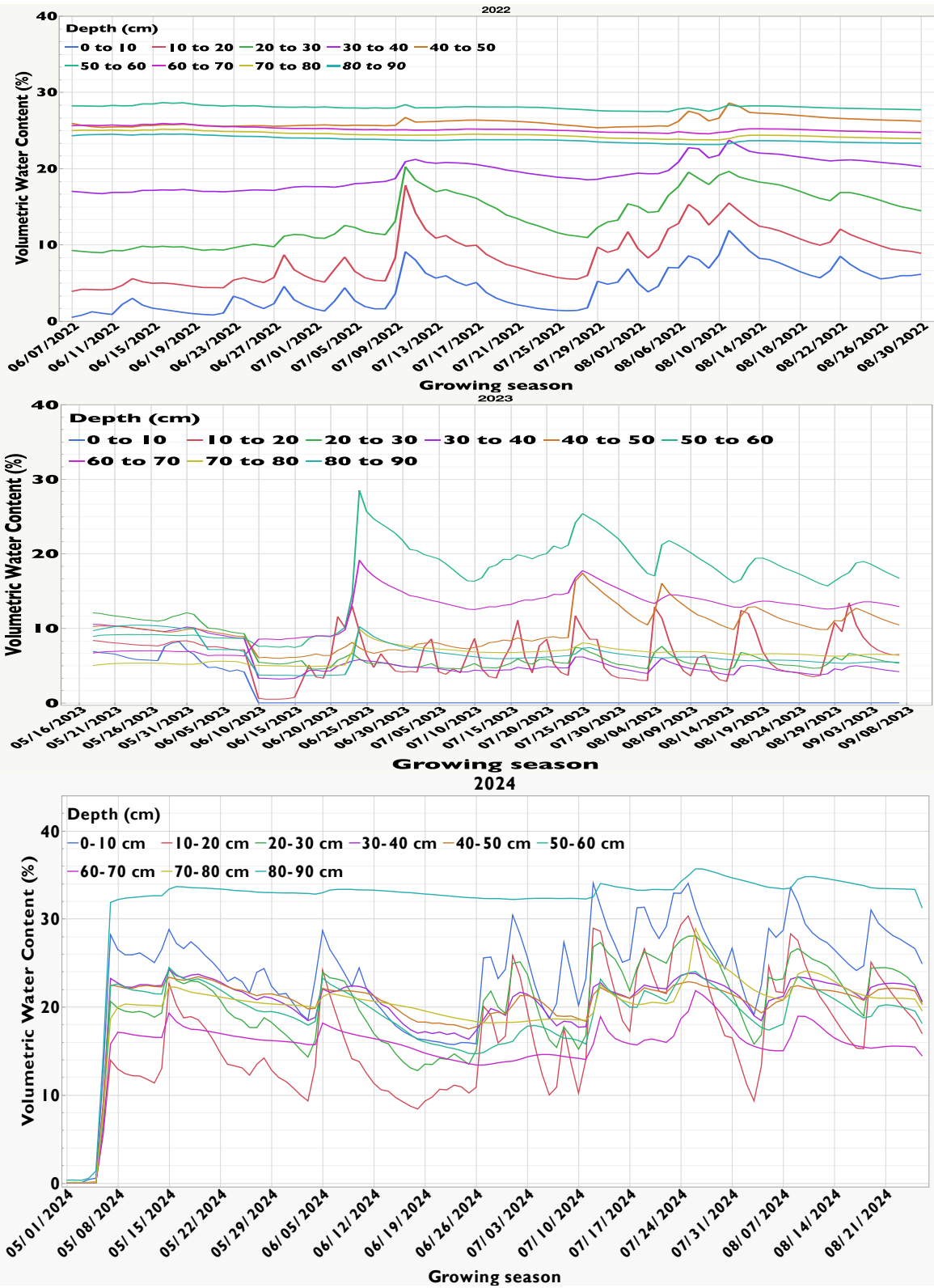


Figure 3.1: Soil volumetric water content for the SDI system in 2022 (top), 2023 (middle), and 2024 (bottom). Data was collected from field sensors using data loggers, which provide continuous monitoring of soil moisture levels at various depths in the root zone.

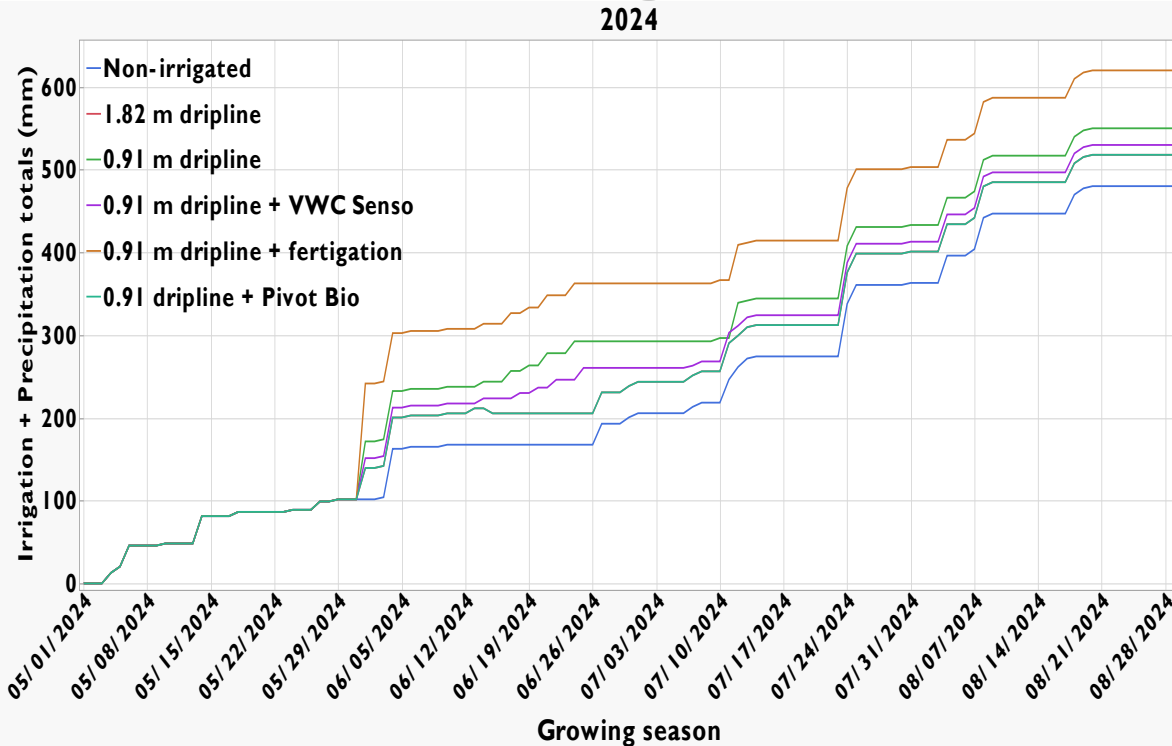
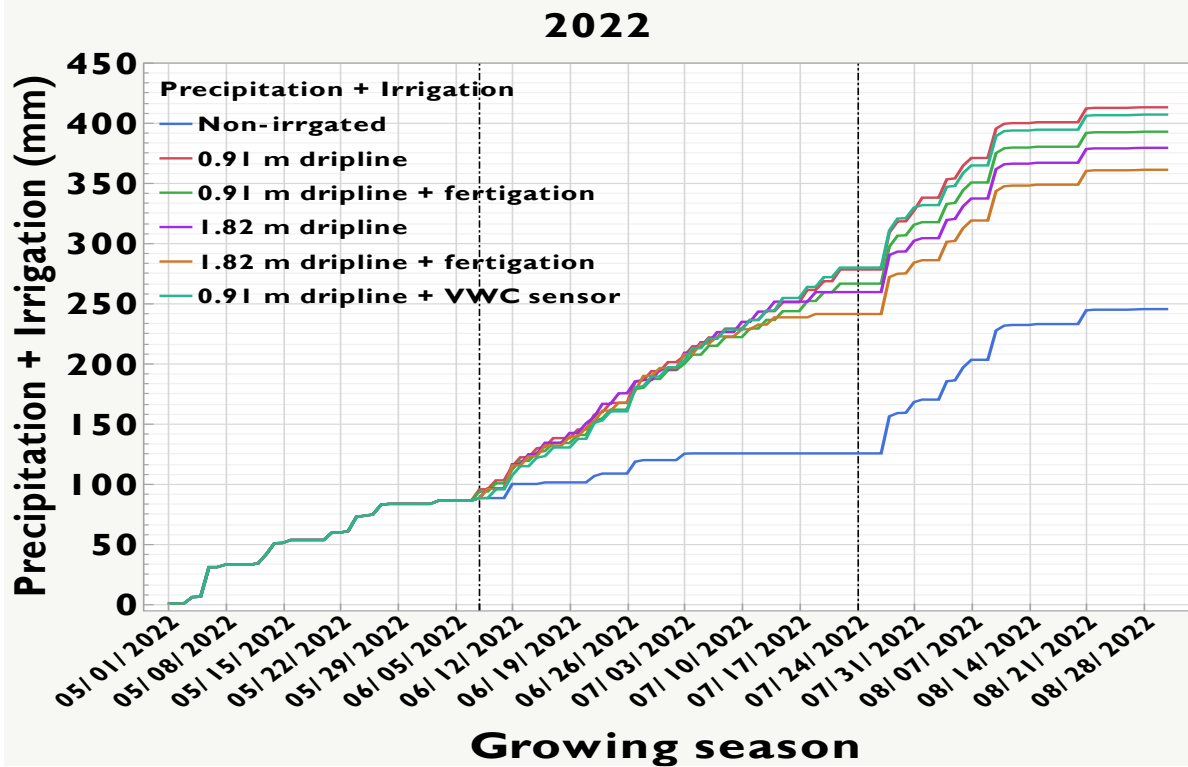


Figure 3.2: Total seasonal moisture (irrigation + precipitation) in 2022, above) and total precipitation + supplemental irrigation for 2024 (bottom) at the Suffolk VA, experimental site. Rainfall data source: [Informet](https://www.informet.com/)

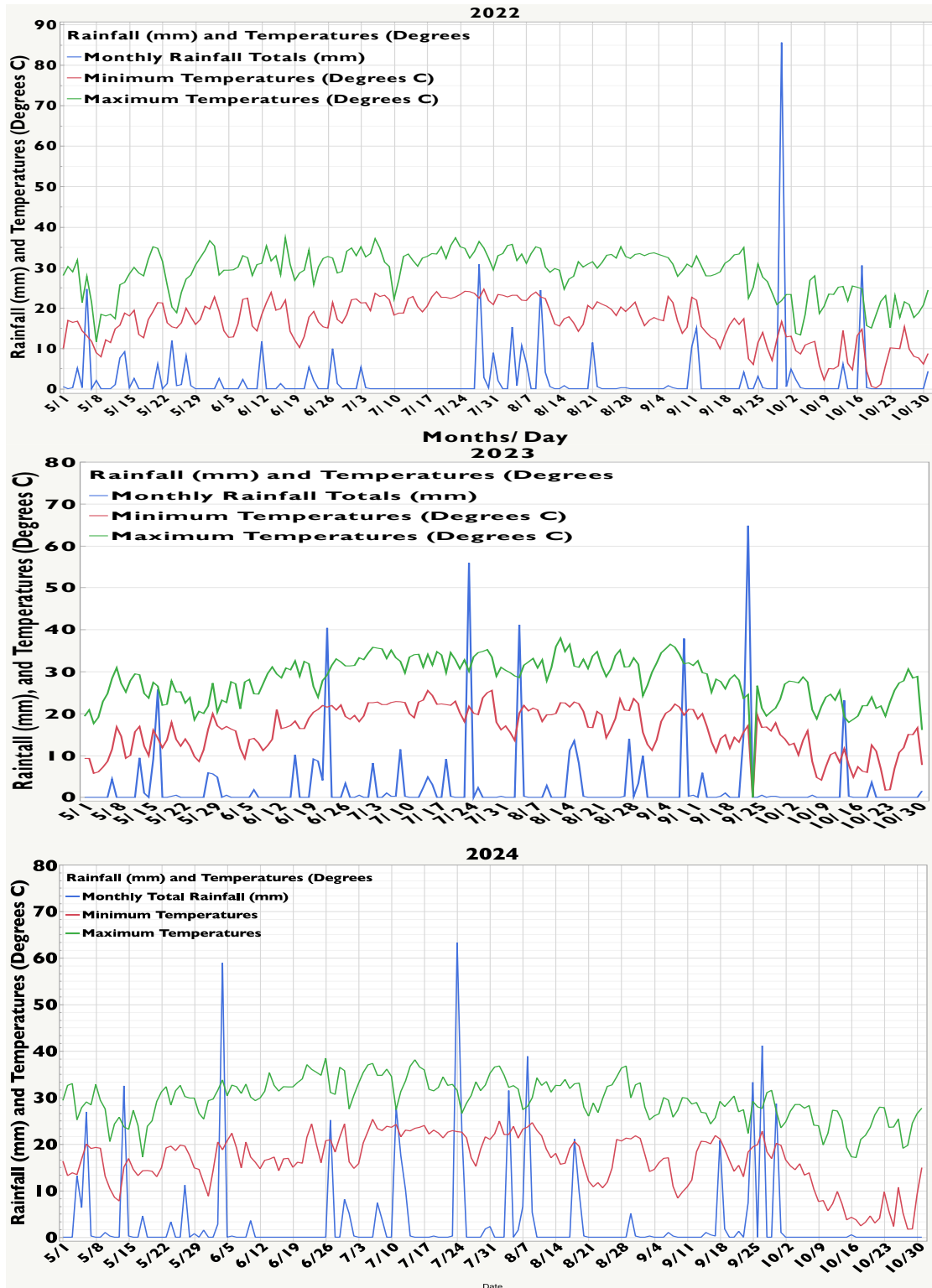


Figure 3.3-a: Weather (Daily Rainfall (mm), Daily Minimum and Maximum Temperatures (°C) from 2022 (above), 2023 (middle) 2024 (below) at the Suffolk VA, experimental site (36° 39' 48.48" N, 76° 44' 10.56" W). Data source: [Infornet](#).

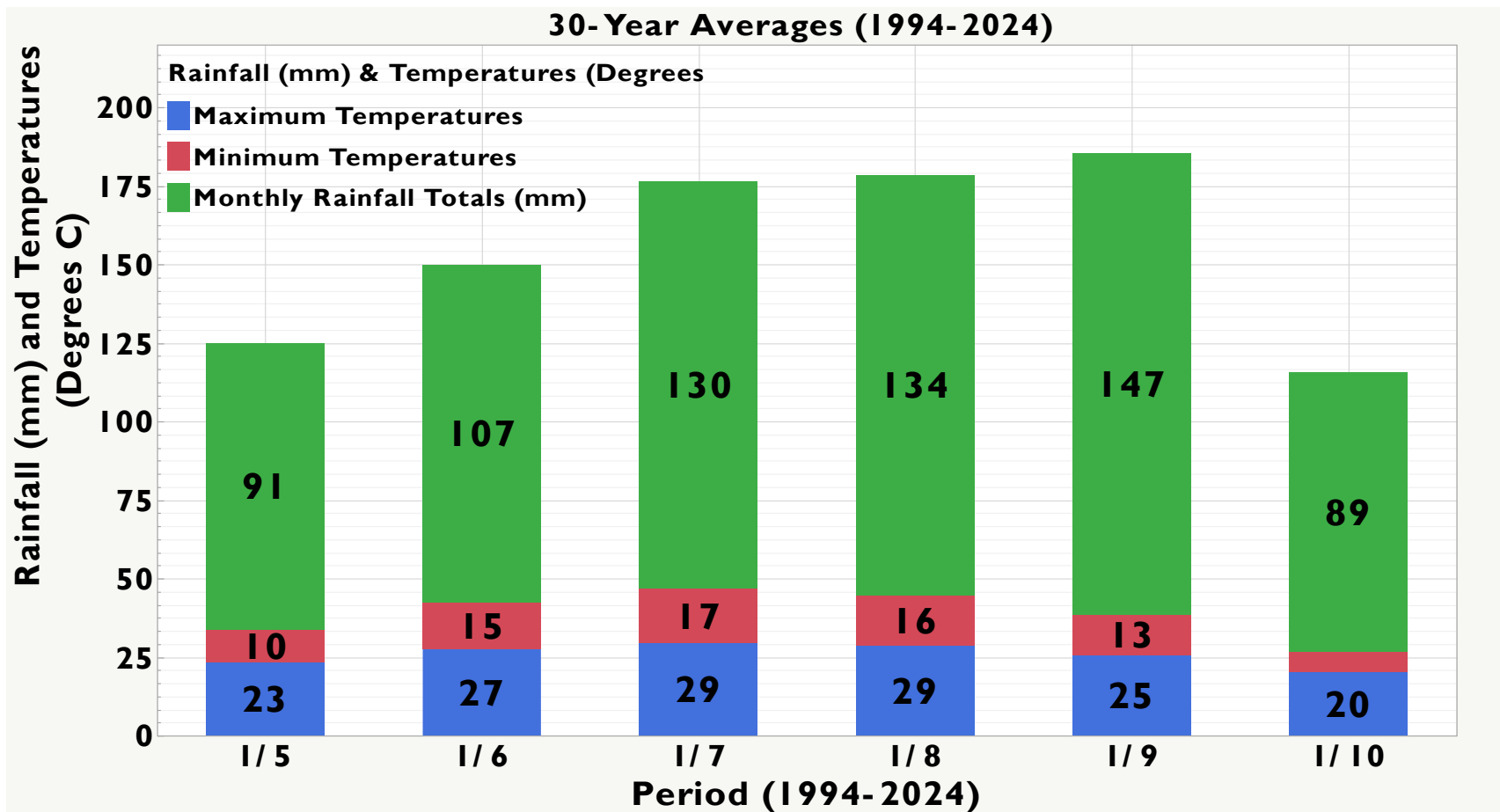


Figure 3.3-b: Long-term average daily weather characteristics at the experimental site in Suffolk VA, from 1994 to 2024. Data from [Infor.net](#)

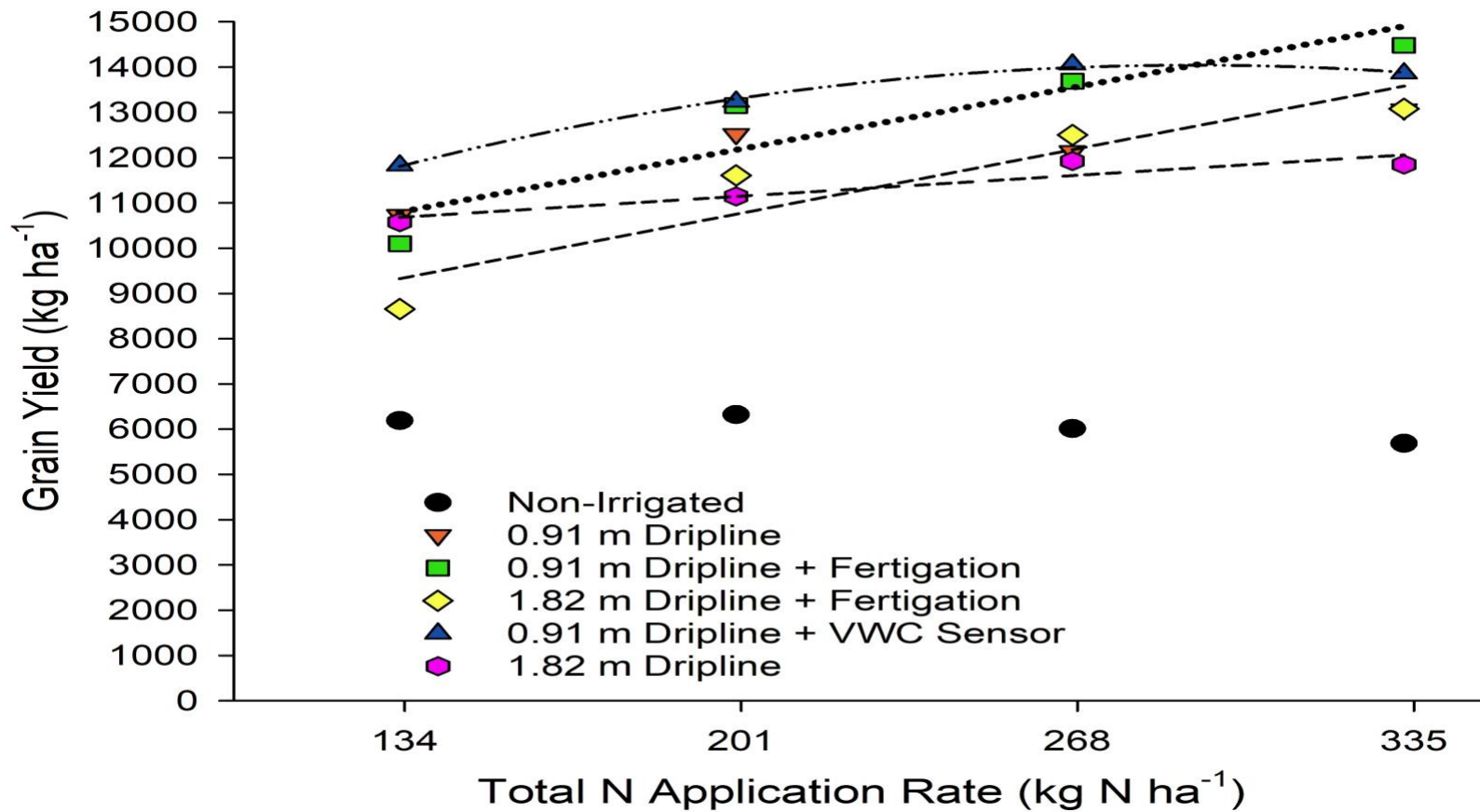


Figure 3.4: Regression of interaction between irrigation and nitrogen rates on grain yield at Suffolk VA, in 2022. Displaying significant positive yield increases with nitrogen rates at all irrigation strategies except non-irrigated (check). A regression line indicates that the regression analysis for the irrigation strategy was significant at alpha = 0.1. No regression for the irrigation strategy indicates the linear regression model was not significant for the irrigation strategy.

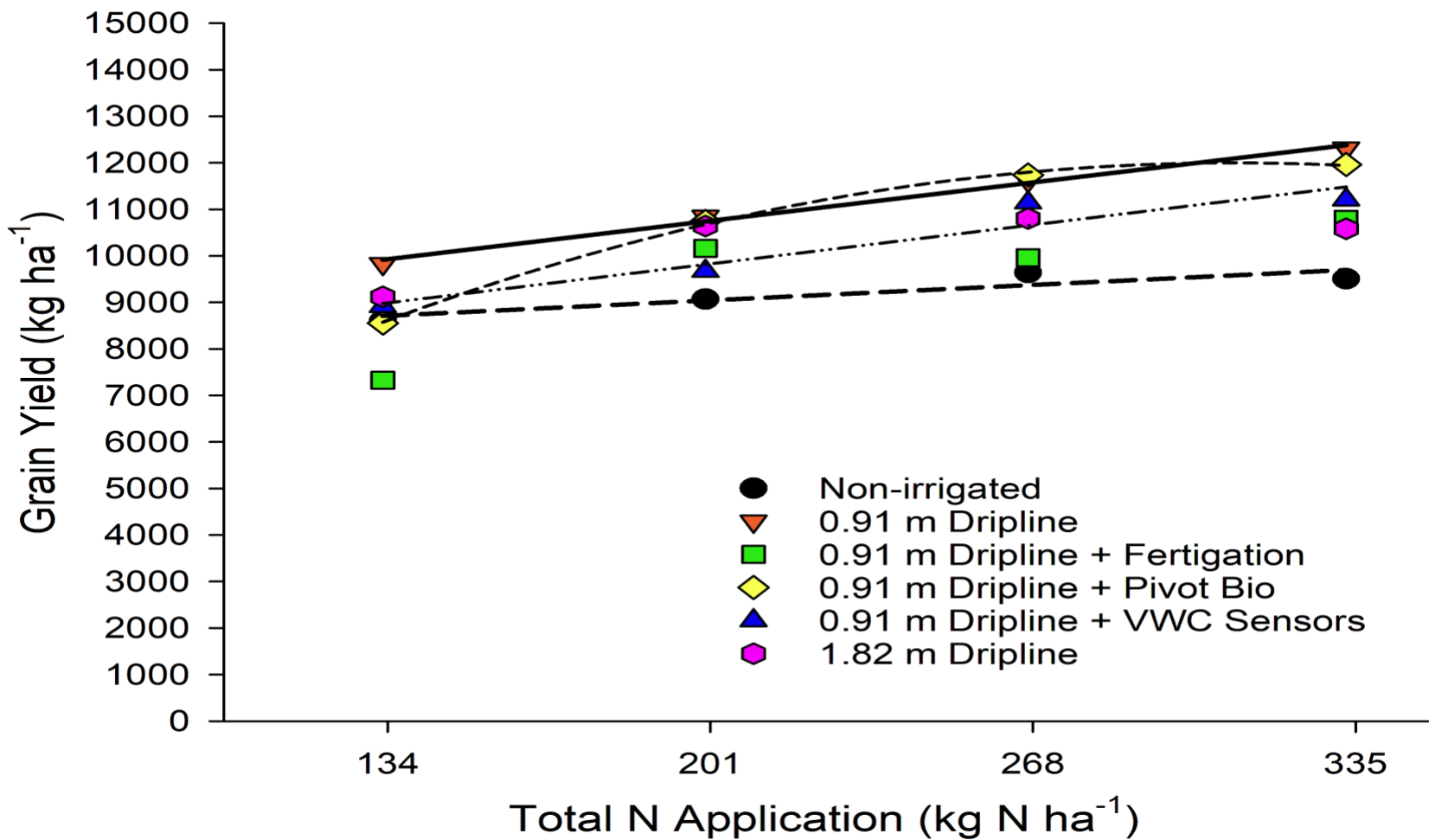


Figure 3.5: Regression of interaction between irrigation and nitrogen rates on grain yield at Suffolk VA, in 2023. A regression line indicates that the regression analysis for the irrigation strategy was significant at alpha =0.1. No regression for the irrigation strategy indicates the linear regression model was not significant for the irrigation strategy.

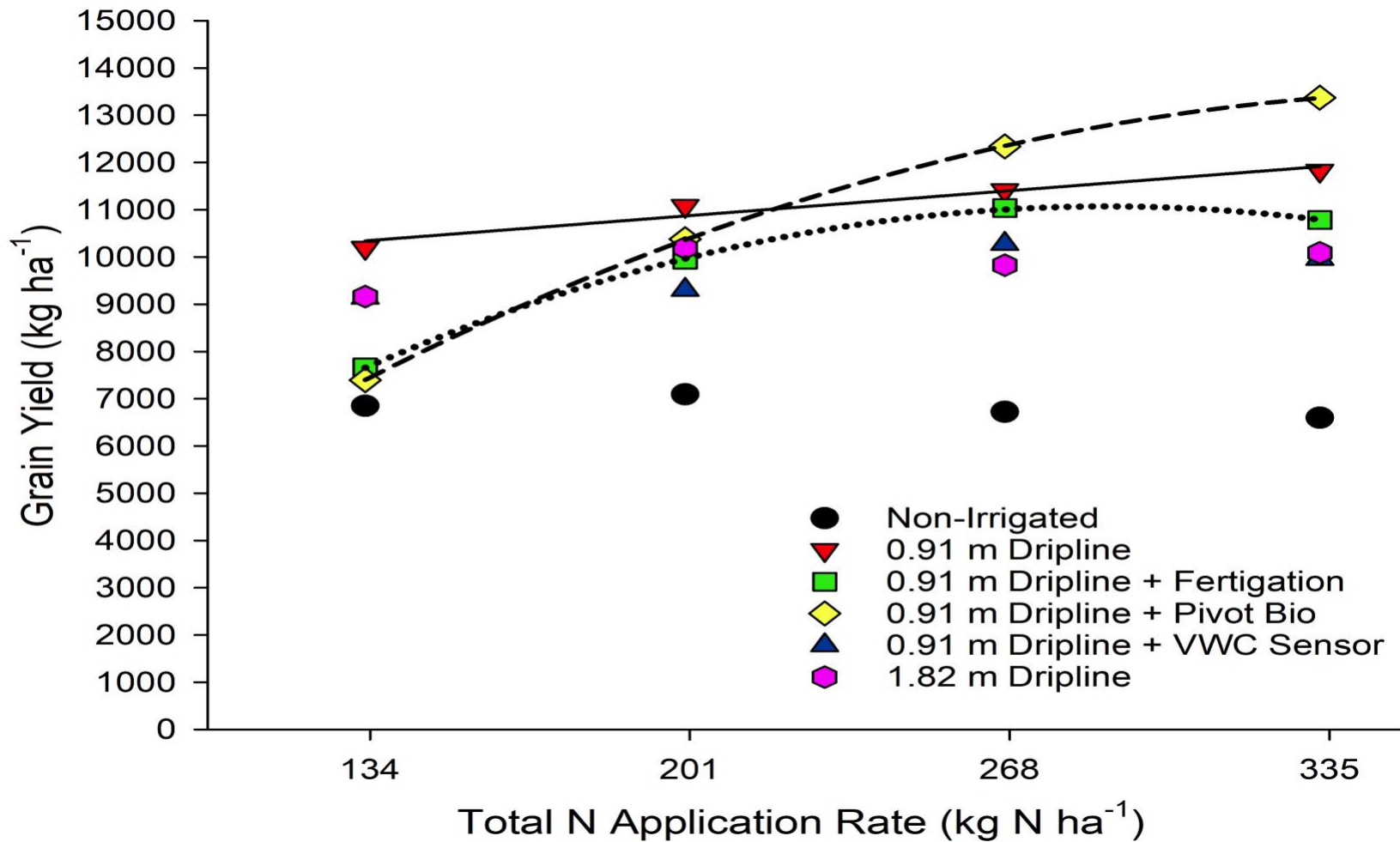


Figure 3.6: Regression analysis of interaction between irrigation and nitrogen rates on grain yield at Suffolk VA, in 2024. A regression line indicates that the regression analysis for the irrigation strategy was significant at alpha = 0.1. No regression for the irrigation strategy indicates the linear regression model was not significant for the irrigation strategy.

Table 3.1: Mehlich-1 Soil Chemical Characterization at Experimental Sites (Zones 1-9 and 10-18) under Subsurface Drip Irrigation System Experiment at Suffolk, VA (2022-2024).

Year	Field	P	K	Ca	Mg	Zn	Mn	Cu	Fe	pH <sup>†</sup>	Est CEC <sup>‡</sup>
		-----kg ha <sup>-1</sup> -----				-----mg kg <sup>-1</sup> -----				1:1	meq/100g
2022	Zone 1 to 9	93	275	1314	158	0.6	5.0	0.1	10.2	6.9	3.9
	Zone 10 to 18	76	259	1144	140	0.5	4.0	0.1	10.3	7.0	3.4
2023	Zone 1 to 9	84	149	1227	163	0.5	5.2	0.1	14.5	6.2	3.6
	Zone 10 to 18	72	98	591	36	0.7	2.4	0.2	13.4	5.7	2.0
2024	Zone 1 to 9	98	114	1038	127	3.8	3.7	0.1	10.7	6.3	3.3
	Zone 10 to 18	93	122	1093	143	3.7	3.5	0.1	11.3	6.4	3.3

<sup>‡</sup>Cation exchange capacity

<sup>†</sup>Soil pH measured using 1:1 of soil to water

Table 3.2: Main effects of SDI irrigation strategies on grain yield and the economic impacts (2022-2024) at Tidewater, Suffolk, VA

Year	2022		2023		2024		22-24		Economics				
Grain yield	Yield	$\Delta$ Yield	Yield	$\Delta$ Yield	Yield	$\Delta$ Yield	$\Delta$ Yield		R <sub>Y</sub>	Revenue	ROI		
	-----Grain yield (kg ha <sup>-1</sup> ) -----										---%---	----\$---	Years
0.91 dripline	12114	c 6060	11152	a 1945	11131	a 4314	4106	0.97	\$985	6.3			
0.91 dripline + Fert	12856	b 6802	9560	e 352	9856	c 3039	3398	0.90	\$816	7.6			
0.91 dripline + Pivot bio	-	-	10750	b 1543	10872	b 4054	2799	-	\$672	9.2			
0.91 + VWC	13248	a 7194	10235	d 1028	9671	e 2854	3692	0.93	\$886	7.0			
1.82 dripline	11374	e 5320	10288	c 1081	9819	d 3002	3134	0.89	\$752	8.2			
1.82 dripline + Fert	11460	d 5406	-	-	-	-	5406	-	\$1297	4.8			
Non-irrigated	6054	f	9208	f	6817	f	-	0.63	-	-			
<b>P-Value</b>	<b>&lt;0.001</b>		<b>0.089</b>		<b>&lt;0.001</b>		<b>&lt;0.001</b>						

Acronyms: Fert = Fertigation, <sup>1</sup>Relative yield. Yield data denoted by different letters indicate significant differences among treatments at P<sub>≤</sub> 0.1. Return on investment is calculated using an assumed irrigation equipment cost of \$6,175 ha<sup>-1</sup> and reflects the average gross revenue per hectare for each strategy at 17¢ kg<sup>-1</sup> of corn grain. Data source: USDA-NASS, 2024.

Table 3.3: A table of interaction between irrigation and seeding rates strategies on grain yield at Tidewater Agricultural Research Center in 2022, in 2022.

Irrigation strategies	Seeding rate strategies			
	59280	74100	88920	103740
	.....Grain yield (kg ha-1) .....			
0.91 + Fertigation	11586 fgh	13241 abc	13252 abc	13345 ab
0.91 + VWC Sensor	11722 efgh	13606 ab	13659 a	14003 a
0.91 dripline	11482 ghi	12473 cde	12174 defg	12327 def
1.82 dripline	10746 ij	11799 efgh	12808 bcd	10141 j
1.82 + Fertigation	11382 ghi	11229 hi	11327 hi	11904 efgh
Non-irrigated	5802 kl	6406 k	6531 k	5477 i

Mean yield in a row across the seeding rates sharing similar letters are not significantly different at  $P \leq 0.1$ .

Table 3.4: Grain yield response to seeding and nitrogen rates strategies from 2022 to 2024 at Tidewater, Suffolk, VA

Main Effects	Year			Relative Yield
	2022	2023	2024	
	-----Grain yield (kg ha <sup>-1</sup> ) -----			-----%-----
<b>Seeding Rate (seed/ha)</b>				
59,280	10,453 b	9,791 b	9,411 b	0.82 b
74,100	11,459 a	9,906 b	9,781 ab	0.87 a
88,920	11,625 a	10,657 a	9,628 ab	0.89 a
103,740	11,199 a	10,441 a	9,957 a	0.88 a
<b>P-value</b>	<b>&lt;0.001</b>	<b>0.044</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>
<b>Nitrogen Application Rate (kg N/ha)</b>				
133	9,681 c	8,727 c	8,402 c	0.77 c
200	11,331 b	10,190 b	9,666 b	0.87 b
267	11,721 ab	10,818 a	10,270 a	0.90 a
333	12,004 a	11,061 a	10,439 a	0.92 a
<b>P-value</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>

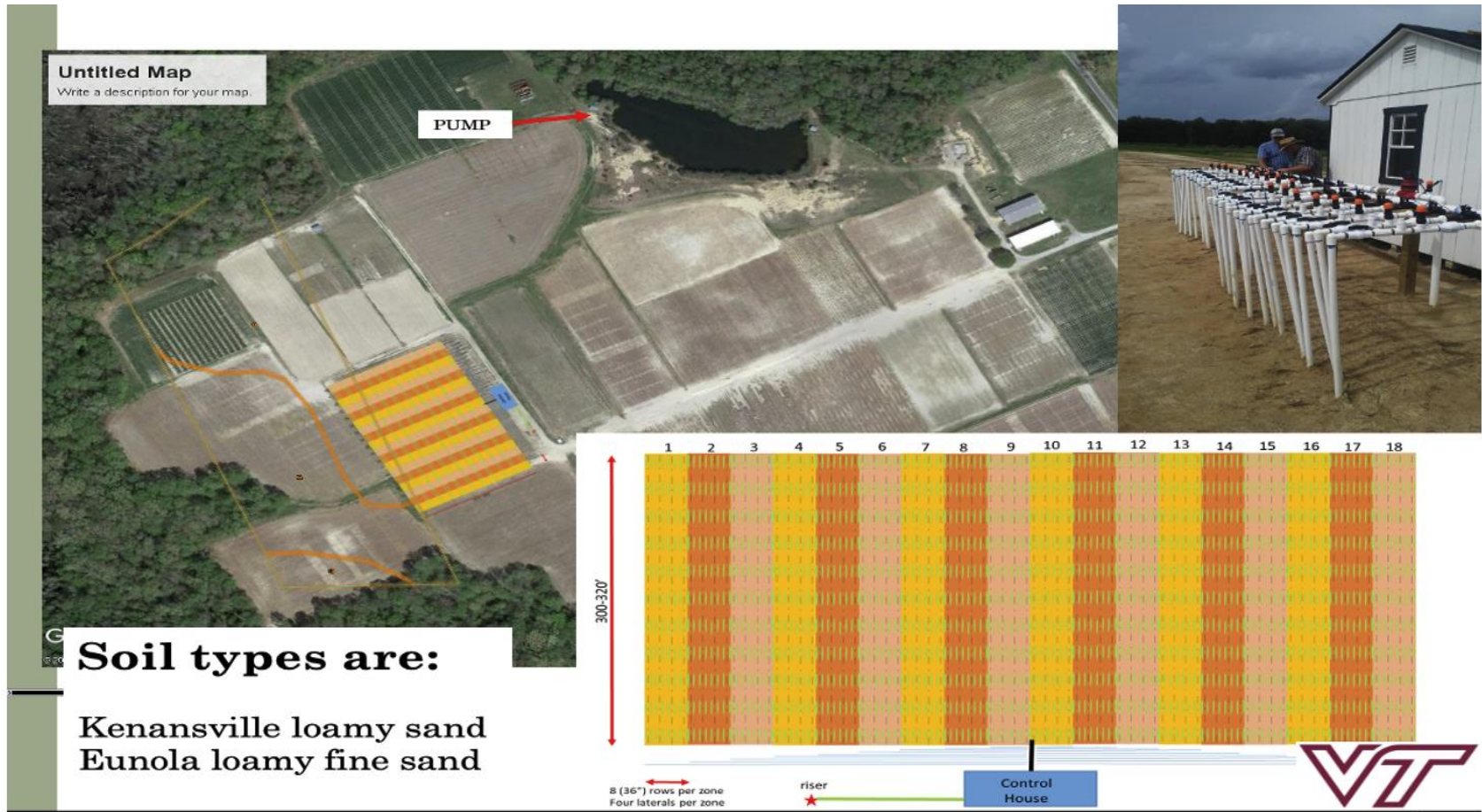
Yield data denoted by different lowercase letters under each year indicate significant differences among treatments at  $P \leq 0.1$  for nitrogen and seeding rates effects.

3-year Avg: Are for compulsions of averages and no statistical significance calculated

Table 3.5: Regression Equations and Statistical Summary for Irrigation Strategies and Nitrogen Rates Interactions determined by quadratic plateau model for three years (2022 to 2024)

<b>Irrigation Strategy</b>	<b>Regression Equation</b>	<b>R<sup>2</sup></b>	<b>P-value</b>
<b><u>2022</u></b>			
Non-Irrigated	$y = 6,689 - 2.7 * Nrate$	0.726	ns
0.91 m Dripline	$y = 9,803 + 9.9 * Nrate$	0.734	ns
0.91 m Dripline + Fertigation	$y = 8,071 + 20.5 * Nrate$	0.851	0.078
1.82 m Dripline + Fertigation	$y = 6,501 + 21.3 * Nrate$	0.867	0.069
0.91 m Dripline + VWC Sensor	$y = 6,463 + 52.1 * Nrate - 0.09 * (Nrate)^2$	0.997	0.057
1.82 m Dripline	$y = 9,766 + 6.8 * Nrate$	0.869	0.068
<b><u>2023</u></b>			
Non-Irrigated	$y = 8,056 + 4.9 * Nrate$	0.726	ns
0.91 m Dripline	$y = 8,280 + 12.3 * Nrate$	0.992	0.004
0.91 m Dripline + Fertigation	$y = 6,002 + 15.3 * Nrate$	0.739	ns
0.91 m Dripline + Pivot Bio	$y = 1,486 + 67.9 * Nrate - 0.11 * (Nrate)^2$	0.998	0.034
0.91 m Dripline + VWC Sensor	$y = 7,314 + 12.52 * Nrate$	0.912	0.045
1.82 m Dripline	$y = 8,693 + 6.84 * Nrate$	0.566	ns
<b><u>2024</u></b>			
Non-Irrigated	$y = 7,213 - 1.7 * Nrate$	0.47	ns
0.91 m Dripline	$y = 9,298 + 7.9 * Nrate$	0.95	0.026
0.91 m Dripline + Fertigation	$y = -687 + 81.5 * Nrate - 0.14 * (Nrate)^2$	0.98	0.016
0.91 m Dripline + Pivot Bio	$y = -1,359 + 80.2 * Nrate - 0.11 * (Nrate)^2$	1.000	0.005
0.91 m Dripline + VWC Sensor	$y = 8466 + 5.17 * Nrate$	0.68	ns
1.82 m Dripline	$y = 8973 + 3.62 * Nrate$	0.46	ns

### Appendix 3



**Figure A3.1** Showing the field experimental site, different components, and arrangement of different irrigation strategies, Pictured at the experimental site at Suffolk VA (36° 39' 48.48" N, 76° 44' 10.56" W), by Dr Frame.



**Figure A3.2** Showing the field observable plant characteristics under different irrigation strategies. Pictured at 36° 39' 48.48" N, 76° 44' 10.56" W - SDI research field.



**Figure A3.3:** Displaying different irrigation zones for Block 2 of the SDI Research Experimental site Pictured at 36° 39' 48.48" N, 76° 44' 10.56" W - SDI research field in June 2024



**Figure A3.4:** Beginning of the early season drought in the second week after fertilizer broadcast, Pictured at 36° 39' 48.48" N, 76° 44' 10.56" W - SDI research field June 2024

#### **4.0. Cotton Response to Subsurface Drip Irrigation, Plant Growth Regulators, and Nitrogen Rates in the Upper Southeast Coastal Plain**

##### **Abstract:**

From 2019 to 2021, two experiments were conducted at the Tidewater Agricultural Research Center (TAREC) in Suffolk to evaluate subsurface drip irrigation (SDI) strategies for upland cotton (*Gossypium hirsutum*). Experiment 1 assessed the effects of three dripline spacings (0.91 m, 1.82 m, non-irrigated), four plant growth regulator (PGR) rates (0%, 100%, 150%, 200%), and four cotton varieties (DP1646 B2XF, PHY340 W3FE, ST5020 GLTP, ST4550 GLTP). Experiment 2 investigated three irrigation strategies (0.91 m dripline, 0.91 m dripline + fertigation, non-irrigated), three nitrogen (N) rates (89, 133, 178 kg ha<sup>-1</sup>), three PGR rates (0%, 100%, 200%), and two varieties (DP1646 B2XF, PHY340 W3FE). In Experiment 1, dripline spacing significantly influenced lint yield in 2020 and 2021, while variety significantly influenced lint yield and lint percentage across all three years. Plant growth regulator application significantly affected lint yield only in 2021 and lint percentage across all years. The 1.82 m dripline and 100% PGR rate achieved the highest lint yields and economic gains (\$158 ha<sup>-1</sup> and \$162 ha<sup>-1</sup> over controls). Experiment 2 found significant effects of irrigation strategies on lint yield across years, with irrigation only outperforming fertigation and non-irrigated cotton in two years. The greatest increase in lint yield was attained at the 133 kg N ha<sup>-1</sup> in 2 of 3 years, and there was no statistical difference between the 133 and 178 kg N ha<sup>-1</sup> rates. For PGR rates, N rates, and variety, each influenced lint yield in 2 of 3 years of the study. Increasing PGR application rates were associated with declining yield and profitability. This study provides

critical insights into integrating SDI with PGR strategies, N management, and variety selection to enhance cotton productivity and economic returns in the Southeast coastal plain.

### **Core ideas**

- Irrigation significantly influenced seed and lint yield in 5 of 6 experiments.
- Upland cotton lint yield varied due to varieties in 5 of 6 experiments.
- The highest lint yield increase was at 1.82 dripline spacing and 100% PGR rate producing \$158 and \$162 in economic returns, respectively.
- The optimal N rate for seed cotton and lint yield was 133 kg N ha<sup>-1</sup>.

#### 4.1. Introduction

In the USA, cotton is an important agronomic crop spanning from Virginia to California and planted on over 4,249,199 million hectares, of which the south-eastern region alone contributes 910,931 hectares according to the 2023/24 cotton outlook (Meyer et al., 2023). In terms of global production, the United States of America (USA) currently ranks fourth with a total of 14.6 million bales of lint and an estimated national average lint yield of 1,059 kg ha<sup>-1</sup> compared to the world average of 792 kg ha<sup>-1</sup> (Meyer et al., 2023). The US is the world's largest cotton exporter, while China is the largest cotton importer (Johnson et al., 2013; Meyer et al., 2023). The key cotton-producing states in the United States include Texas, which accounts for over 40% of the USA's cotton production, followed by Georgia, and Mississippi (Meyer et al., 2023). In Virginia, 36,000 hectares of cotton were harvested in 2022-2023 (USDA-NASS, 2024). Only 15% of U.S. cotton is irrigated which is primarily concentrated in Texas with <5% of the Virginia cotton acres irrigated (Johnson et al., 2020; US-Census, 2018). Irrigation in Virginia has the potential to significantly improve cotton yields; however, implementing a water-efficient and adaptable system is essential to optimize resource use and ensure sustainability.

The growth and yield of cotton are contingent upon genotype (varieties), environmental factors (soil type, temperature, rainfall), and agronomic management strategies. Effective irrigation management strategies will be needed to combat changing climatic conditions (i.e. increasing sporadic precipitation events, and higher average temperatures) (Nguyen et al., 2023). Maintaining adequate soil moisture through irrigation is vital for cotton production, as it directly influences nutrient absorption, photosynthesis, and overall plant growth (Ullah et al., 2019). This is particularly important in the Southeast region, where the soils are largely sandy and with low water holding capacities thus prone to drought (DCR, 2024). With increasing sporadic rainfall,

drought stress may become yield limiting even in crops that were thought to be drought tolerant. In West Texas, the leading cotton production region, cotton suffered due to drought resulting into that region's largest crop loss during the 2022 – 2023 crop years (Meyer et al., 2023). In response to climate crisis, many governments tend to adopt water conserving strategies with evolving legal and regulatory frameworks (Brown et al., 2019). For VA, the Virginia Department of Water and Environmental Quality (VA-DEQ) require special permits for groundwater withdraw beyond 300,000 gallons per month where users must secure a license (VA-DEQ, 2024; NASS, 2024).

With less than 5% of Virginia's cropland irrigated, there is limited information on the appropriate irrigation strategies and systems for managing upland cotton in Virginia. For other cotton producing regions, research has documented irrigation markedly enhances seed cotton yield, lint percentage, and boll density, albeit with potential reductions in boll weight and seed index in irrigated scenarios (Ren et al., 2013). This underscores the necessity for selecting cultivars that are well-suited for either irrigated or dryland cultivation. Furthermore, recent simulated research utilizing the CSM-CROPGRO-Cotton model reveal that non-irrigated cotton yields fall by over 10% in more than 70% of the analyzed site-years compared to fully irrigated cotton, thereby demonstrating the economic viability of irrigation (Spivey et al., 2018). Research conducted at Clemson University identified advantageous genetic traits, which enhance water use efficiency and drought tolerance. This suggests that breeding initiatives could focus on these traits to develop cotton varieties tailored for irrigation in the southeastern U.S. (Spivey et al., 2018). To optimize cotton yields in Virginia and other southeastern states, the exploration of water-efficient and adaptable irrigation systems is imperative to mitigate challenges related to timing and resource utilization.

The subsurface drip irrigation (SDI) could a viable alternative to the more prevalent center pivot irrigation systems used in row crop production systems across the U.S. (Yonts et al., 2000; Lamm et al., 1997; Cahn and Hutmacher, 2024). Subsurface drip irrigation effectiveness is related to several factors, but the most important one is dripline spacing (Cahn and Hutmacher, 2024). The dripline spacing influences the wetted area in the soil profile, which affects plant available water. However, this also varies by soil type and root expansion of the individual crop grown (Enciso–Medina et al., 2002; Sorensen et al., 2022; Cahn and Hutmacher, 2024). Adequate moisture in the root zone directly impacts root absorption, boosting growth and yield by aiding nutrient uptake, enhancing biomass accumulation, chlorophyll development, and photosynthesis (Enciso-Medina et al., 2002).

Cotton is characterized by an indeterminate growth habit, which allows it to grow to heights of 4.7 to 6.1 meters under optimal moisture and nutrient conditions (Ning et al., 2024). However, excessive vegetative growth can lead to dense canopies, high fruit shedding, and reduced yield and fiber quality (Jalilian et al., 2023). To address these challenges, farmers commonly use plant growth regulators (PGRs), a group of synthetic plant hormones that influence plant growth and development. These hormones regulate physiological processes such as cell elongation, resulting in shorter, more compact plants that are better able to utilize environmental resources such as light, carbon, and nutrients (Arekhi et al., 2023; Chalise et al., 2022). The primary PGR utilized for in-season management in cotton is mepiquat chloride (MC). Mepiquat chloride works by inhibiting gibberellin biosynthesis, a hormone responsible for promoting stem elongation, thereby resulting in shorter, sturdier plants with increased reproductive structures and enhanced cotton fruit retention (Chalise et al., 2022; Murtza et al., 2022; Arekhi et al., 2023). The effectiveness of PGRs depends on the application rates, as well as

the growth characteristics of the cotton cultivars. Modern cotton varieties exhibit diverse genetic traits that affect their response to PGRs, necessitating the evaluation of growth regulators on current commercial varieties to optimize their use (Han et al., 2022; Murtza et al., 2022). Strategic PGR application at specific growth stages, in conjunction with appropriate irrigation, and nitrogen (N) management, can significantly result into enhanced growth and yield (Arekhi et al., 2023; Chalise et al., 2022). But the response of cotton under the subsurface drip irrigation system to PGR management is not known in the Upper Southeast Coastal Plain region.

Growth of cotton is largely tied to N availability in the soil (Fageria and Baligar, 2005; Main et al., 2014). All N required for cotton needs to be supplied as amendments. Current cotton N management is based on the 56 kg N per bale of cotton (218 kg of cotton lint) (Main et al., 2014). The common cotton rates in the Southeast Coastal Plains have been refined to be 80 to 133 kg N ha<sup>-1</sup> with the optimal rates being 133 kg N ha<sup>-1</sup> (McClanahan et al., 2020). The optimal moisture and N levels available in the soil can enhance cotton plant growth and yield parameters like boll retention. However, excessive available N can lead to issues like reduced boll formation, excessive plant growth, and reduced yields (Enciso-Medina et al., 2002; Ullah et al., 2019; Právělie et al., 2021). A closer relationship between N availability and irrigation response to growth and yield have been reported in many studies. (Arekhi et al., 2023; Chalise et al., 2022; Hussain et al., 2020; Jia et al., 2024)

Although significant progress has been made in irrigation and nutrient management, their combined effects on cotton growth and yield in the Upper Southeast Coastal Plain remain uncertain. Understanding how water availability, N, PGRs and their interactions affect upland cotton performance is crucial for developing tailored management strategies for SDI systems in Virginia and other U.S. cotton regions. Two research studies were initiated to develop

recommendations for upland cotton using SDI in the Upper Southeast Coastal Plain. The objectives of these studies were: 1) To evaluate the effects of different dripline spacings and plant growth regulator (PGRs) management on the growth and yield performance of selected contemporary cotton varieties; and 2) To assess the impact of SDI in conjunction with N application rates, PGR application rates, and cotton varieties on upland cotton yield and economic returns.

## **4.2. Materials and Methods**

### **4.2.1. Site and irrigation system**

Two experiments were conducted over three years (2019-2021) at the Tidewater Agricultural Research and Extension Center (TAREC) in Suffolk, Virginia (36° 39' 48.48" N, 76° 44' 10.56" W). The soils at the experimental site were largely Eunola loamy fine sand (78.8% of study area) with the remaining being Kenansville loamy sand (21.2%). Mehlich I extractable nutrients for both experiments can be found in Table 4.2. The first experiment evaluated the effect of dripline-spacing, PGR application rate, and cotton variety on lint yields and economic returns (Experiment 1) and the second experiment evaluated SDI with and without fertigation, PGR application rate, and cotton varieties on cotton lint yield and economic return (Experiment 2). The SDI system was installed in 2017 and covers a total area of 1.4 hectares. The system has 18 zones with driplines spaced at 0.91 m with the capability to close/shut off every other dripline to evaluate dripline spacings of 0.91 and 1.82 m. The driplines were 15 mil thick and were manufactured by Toro Micro-Irrigation (The Toro Company, Bloomington, Minnesota, USA) with emitters approximately 40.6 cm apart, and a flow rate of 0.6 liters per hour for each emitter. Driplines were buried 25-cm deep and under the row middles. A Netafim

NMC DC controller (Netafim Ltd., Tel Aviv, Israel) was used to automate irrigation events for different irrigation management strategies. Irrigation amounts were controlled via timed irrigation events and a Netafim Octave flow meter logged total gallons of water applied during each irrigation cycle. The 18 zones were divided in half between experiments 1 and 2. Each zone measured 97.5 m in length and 7.31 m in width (eight rows (0.91 m row width)).

Experiment 1 followed a split-split-plot design with irrigation strategies as the whole plots. Irrigation strategies were non-irrigated, 0.91 m dripline spacing, and 1.82 m dripline spacing. Sub-plot treatments were PGR application rates of no PGR, 100%, 150%, and 200% of Virginia Cooperative Extension recommendations for upland cotton (Frame et al., 2016). Sub-plots measured 17.37 m in length and 7.31 m in width (eight rows). Sub-sub-plots were four upland cotton cultivars (Deltapine1646 B2XF (all years), Deltapine 2115 B3XF (2021), Deltapine 2038 B3XF (2021), Phytogen 350 W3FE (2020) Phytogen 340 W3FE (2019 and 2020), Stoneville 5020 GLTP (2019), and Stoneville 4550 GLTP (all years)). Cotton varieties were selected based on performance in the Virginia cotton variety testing program in the previous year and estimated planting acreage for Virginia. The sub-sub-plots were 7.62 m in length and 3.66 m in width (4 rows).

Experiment 2 (dripline-fertigation) evaluated three irrigation strategies including a non-irrigated control, irrigation with the 0.91 m dripline, and irrigation with 0.91 m dripline with fertigation. For the fertigation treatment, 89 kg N, 11 kg S, and 44.5 K<sub>2</sub>O kg ha<sup>-1</sup> were injected with irrigation water over 8 weeks starting from the first square cotton growth stage. Irrigation whole plots were the same size as irrigation zones mentioned previously (97.5 m in length and 7.31 m in width (eight rows (0.91 m row width)). The sub-plot used a factorial arrangement with three N application rates (89, 133, and 178) and three PGR rates (0, 100, and 200%), respectively

(Table 4.1). The sub-plots were 7.62 m in length and 7.31 m in width (eight rows). In the sub-sub-plots of experiment 2, two cotton cultivars (Deltapine 1646 B2XF, and PhytoGen 340 W3FE) were selected. The sub-sub-plots were 7.62 m in length and 3.66 m in width (4 rows).

#### **4.2.2. Experiment management, fertility, and PGR management**

Both experiments were planted on April 30<sup>th</sup>, May 26<sup>th</sup>, and May 13<sup>th</sup> for 2019, 2020, and 2021 respectively (Table 4.1). The irrigation management schedule utilized the checkbook method (Gu et al., 2020). Both studies had an initial pre-plant application of 33 kg N ha<sup>-1</sup> across all treatment groups, followed by the remaining N applied using a subsurface N banding implement utilizing liquid sources of ammonium thiosulfate (ATS) and urea ammonium nitrate (UAN) during sidedressing at matchhead square except the fertigation study. For the fertigation study, fertigation processes were initiated at the first square applying 11 kg N ha<sup>-1</sup> weekly for 8 weeks totaling to 89 kg ha<sup>-1</sup>, and the balance applied as a single sidedress for the respective treatments. Phosphorus and potassium were applied at planting according to Virginia Cooperative Extension soil test recommendations for cotton. Plant growth regulator was applied as a 4.2% formulation of mepiquat chloride at rates of 0, 100%, 150%, and 200% of Virginia Cooperative Extension recommendations for upland cotton (Abaye et al., 2023). Application rates and timings are in Table 4.1. A CO<sub>2</sub> pressurized unicycle sprayer was used to apply treatments with a boom of 7.62 m in width and an application volume of 140 L ha<sup>-1</sup>.

#### **4.2.3. Data Collection and Data Analysis**

Trials were defoliated when approximately 60% of the harvestable bolls were open. A two-row cotton picker (CASE 1822 Cotton Express, manufactured by Case IH) modified with an onboard weighing system was used to harvest and weigh the two center rows of each plot and

lint yield was calculated as percentage lint turnout after ginning. Data were analyzed using split-split-plot design in R studio version 4.4.1 using a mixed model ANOVA at a p-value of 0.1. The model utilized was  $\text{Lint yield} \sim \text{dripline spacing} * \text{PGR rate} * \text{Variety} + \text{Error}$  (Block/irrigation rate) for experiment 1, and  $\text{lint yield} \sim \text{irrigation} * \text{PGR rate} * \text{variety} * \text{N rate} + \text{Error}$  (block/irrigation rate) was used for experiment 2. In these models, dripline spacing, PGR rate, variety, and N rate were fixed factors, while blocks account for the random effects. JMP®, Version 18 (SAS Institute Inc., Cary, NC, 1989-2023) was utilized for graphical presentations for significant interactions. The impact of irrigation and PGR was calculated by comparing yield of the non-irrigated and the no PGR control with PGR rate treatments to estimate the cost-benefits of applying these treatments. The average price of \$1.51 kg<sup>-1</sup> of cotton was accessed from USDA-NASS, 2024 for the period (2019-2021) to calculate the profitability of these treatments.

#### **4.3.0. Results and Discussions**

##### **4.3.1. Environmental conditions at the experimental site/period**

The weather during the growing seasons varied greatly across 2019, 2020, and 2021, influencing cotton growth and the experimental outcomes (Figures 4.1 and 4.2). The 2019 and 2020 growing seasons had early wetness, followed by drier periods, which led to poor initial growth. In contrast, 2021 experienced lower early-season rainfall (<10 mm) on average daily, extending over a prolonged period.

## **4.3.2. Effect of irrigation, variety, and PGR rate strategies on cotton yield and quality in Experiment 1**

### **4.3.3. Irrigation**

Irrigation significantly influenced lint yields during the drier growing seasons of 2020 and 2021 (Table 4.3). Water availability is critical during cotton's boll development stage, when evapotranspiration is at its peak, as this phase determines boll retention and overall yield potential (Schaefer et al., 2018). During these years, yields varied from 1,370 kg ha<sup>-1</sup> (2020) to 2,364 kg ha<sup>-1</sup> (2021). Excessive irrigation during this stage, however, can lead to boll abortion and reduced yields (Guinn, 1982). The 0.91 m dripline irrigation system increased soil moisture and nutrient availability, which, when combined with precipitation, potentially oversaturated the root zone, contributing to fruit shedding and limiting yield improvement. This explains the higher response to irrigation in the drier year as compared to the wetter year, and overall poor response to irrigation due to the weather influence. Ren et al., 2013 observed similar effects of weather and related the poor yields to the impact of weather.

### **4.3.4. PGR rates**

The application of plant growth regulators (PGRs) significantly impacted lint yields only in 2021 but affected percentage lint turnout across the years at  $p \leq 0.1$ . The PGR application rate of 100% (Table 4.1) produced the greatest lint yield of 2,377 kg ha<sup>-1</sup> although this was comparable to that of 150% which recorded 2,288 kg ha<sup>-1</sup>. A significantly higher percentage lint turnout was observed at no PGR in two of the three years (2020 and 2021), with no differences observed at the 100 to 200% PGR application rates in the lint turnout. Applying PGR on moisture stressed cotton can cause reduced growth and yield, similar to excessive or no

application of PGR, (Hand et al., 2022). It's not surprising that most of the treatments that had higher turnout had relatively poor performance in lint yield. This is consistent with Ren et al. (2013), who found that applying PGR reduced boll retention but increased boll sizes (Ren et al., 2013). Hence, careful consideration of PGR usage is essential in cotton cultivation to maximize lint yield.

#### **4.3.5. Varieties**

Cotton variety significantly impacted yield all three years (Table 4.3). Note that varieties changed from season to season because they were selected based on their performance in the previous Virginia Cotton OVT program. The new varieties that performed well in the OVT and were predicted to gain market share were selected and included in the study. The variety ST4550 GLTP outperformed all the rest in lint yield in the first and second year of the study, recording 2,727 and 1,680 kg ha<sup>-1</sup> in 2019 and 2010 respectively. However, when new variety DP2115 B3XF was added in the trial in 2021, it outperformed all of them reaching the overall greatest lint yield of 2,423 kg ha<sup>-1</sup> although this yield was similar to DP 2038 B3XF, which yielded 2,373 kg ha<sup>-1</sup> of lint (Table 4.3). Both varieties have shown strong performance across regions, with superior yields likely resulting from their genetic adaptability and responsiveness to inputs, as supported by Jordan Jr (2021) and Bourland et al. (2023), which highlight their performance under intensive practices in Alabama and Arkansas. These studies indicate that responsiveness to irrigation significantly contributes to the yield potential of these cultivars. These results highlight the benefits of selecting high-yielding cotton varieties, alongside tailored nutrient, and irrigation strategies for enhancing productivity.

#### **4.3.6. Economic Analysis for Experiment 1**

The economic analysis of irrigation and plant growth regulators rates in cotton production was calculated considering the average performance across the three years (Table 4.4). The analysis of dripline spacing showed that a 0.91-meter dripline increased yields by 54 kg ha<sup>-1</sup>, generating an economic benefit of \$81, while the 1.82-meter spacing produced a higher yield increase of 105 kg ha<sup>-1</sup> and an economic benefit of \$158 (Table 4.4). The PGR component showed that the 100% PGR led to the greatest yield increase of 107 kg ha<sup>-1</sup>, equating to an economic benefit of \$162 above untreated check which was the greatest compared to other rates. The application of a 150% PGR rate resulted in a yield boost of 68 kg ha<sup>-1</sup>, with an economic benefit of \$102, while the PGR rate of 200% produced only 17 kg ha<sup>-1</sup> above untreated translating to the least economic benefit of \$26 (Table 4.4). Overall, the PGR rates higher than 100% of the Virginia Cooperative Extension recommendation resulted in reduced economic benefits.

#### **4.3.3. Effect of fertigation, variety, PGR rate, and nitrogen rate strategies on cotton yield in Experiment 2.**

##### **4.3.3.1. Irrigation**

Yield response to irrigation varied across years, with the highest benefits observed in 2019 and 2020. This difference can be attributed to gaps in precipitation observed in June 19 to June 26<sup>th</sup>, July 4<sup>th</sup> to 31<sup>st</sup>, and September 11 to September 25<sup>th</sup> in 2019, and June 26<sup>th</sup> to July 3<sup>rd</sup>, July 10<sup>th</sup> to July 17<sup>th</sup> in 2020. Irrigation during these critical growth stages (squaring to blooming) can increase squaring and blooming as well as boll retention that are critical yield traits (Guinn, 1982). These sporadic rainfall patterns meant that non-irrigated plots experienced

moisture stress during the squaring and blooming leading to reduced yield compared to irrigated treatments. In contrast, the 2021 season had higher rainfall peaks in July to August with some reaching >50mm of daily rainfall totals (Figure 4.1), which explains why the observed yields with irrigation were significantly lower compared to non-irrigated yields. Lint yields were highest in 2019 and 2020 under irrigation, demonstrating the benefits of supplemental water during those years. In 2021, the non-irrigated treatment outperformed the irrigated treatments, reaching 1,650 kg ha<sup>-1</sup>, likely due to heavy rainfall that offset dry periods and provided consistent water supply during critical cotton growth stages. The relatively low response to fertigation suggests that the timing and amount of nutrients delivered through this method might not have aligned perfectly with plant needs during peak growth. As Schaefer et al. (2018), and Hussain et al. (2020) observed, cotton's nutrient demand intensifies during certain growth phases, while moisture demands are critically between first square and full bloom. So, if irrigation or fertigation does not adequately meet these demands, yield responses are limited.

#### **4.3.3.2. PGR rates**

The application of PGR influenced lint yield and lint turnout in 2019 and 2021, while in 2020, only percentage lint turnout was influenced. The greatest lint yield and percentage turnout in 2019 and 2021 was recorded either at 0 or 100% PGR (Table 4.5). In two of the three years (2019 and 2021), 0 and 100% PGR rates produced statistically same results in lint yield and lint turnout. However, the 200% PGR rate consistently resulted in the least lint yield compared to the 0-100% PGR. These findings align with prior research by Ren et al. (2013), which highlighted that the effectiveness of plant growth regulators (PGRs) is highly dependent on the rates applied and environmental conditions during application. Similarly, Murtza et al. (2022) and Arekhi et al. (2023) demonstrated that PGR effectiveness varies with factors such as soil moisture, nutrient

availability, and cotton growth stages, emphasizing the need for precise management tailored to specific growing conditions.

#### **4.3.3.3. Nitrogen rates**

Like PGR application rate treatments, N application rates influenced seed cotton and lint yield only in 2019 and 2021 (Table 4.5). However, a positive trend of increasing yield with increasing N rates was consistent in all the three years (Table 4. 5). The greatest yield was reached using the 178 kg N rate applied in 2019, (1,699) but this was statistically similar to 1,614 kg ha<sup>-1</sup> lint recorded at 133 kg N ha<sup>-1</sup> in the same year. In 2021, the 133 kg N ha<sup>-1</sup> recorded the greatest lint yield (1,604 kg ha<sup>-1</sup>) which declined at the highest N rate of 178 kg N ha<sup>-1</sup>. No statistically significant differences were observed due to N application rates in 2020, although the highest lint yield was observed when the 133 kg N ha<sup>-1</sup> was applied. These results of N rate response to N rates are similar to those of McClanahan et al. (2020) which found the greatest performance of cotton cultivars in lint yield at 133 kg N ha<sup>-1</sup> in the soils of Southeast costal Virginia.

#### **4.3.3.4. Varieties**

Cotton variety significantly influenced lint yield in both 2020 and 2021 but influenced percentage lint turnout in 2019 and 2021 (Table 4.5). The variety DP1646 B2XF demonstrated superior performance in 2020, producing the highest lint yield of 1,475 kg ha<sup>-1</sup>, while ST4550 GLTP produced the highest lint yield of 1,578 kg ha<sup>-1</sup> in 2021. The variation in variety performance across years underscore the importance of varietal selection in response to environmental conditions and management practices to maximize cotton productivity. Similar varieties showed greater performance in recent cultivar evaluation programs conducted in

Alabama and Arkansas, where they consistently showed superior yields under varying conditions (Jordan Jr., 2021; Bourland et al., 2023). This indicates the varieties high genetic attributes for performing under diverse environmental conditions.

#### **4.3.3.5. Economic analysis of PGR rates and irrigation strategies on the profitability of cotton in Experiment 2.**

The economic evaluation of irrigation and fertigation, and PGR in fertigation experiment for optimizing yield and profitability was averaged across all 3 years of the experiments.

Irrigated treatments averaged 21 kg ha<sup>-1</sup>, above non-irrigated, leading to an economic benefit of \$32 (Table 4.6). Conversely, fertigation with deficit irrigation decreased yield resulting in an economic deficit of \$-49. In terms of PGR, the variations due to the rates applied was observed only in 2019 and 2021. Averaged over the three years, PGR application resulted in an economic deficit of \$-23 and \$-118 when 100% and 200% PGR rates were applied compared to the untreated check. Overall, results indicated limited economic advantages of fertigation, and no benefit of PGR application in experiment 2 (Table 4.6).

#### **4.4: Conclusions.**

This study demonstrates the potential for integrating subsurface drip irrigation (SDI), plant growth regulator (PGR) strategies, and nitrogen (N) management, in modern cotton varieties selection to optimize cotton production systems in the upper Southeast Coastal Plains. The 1.82-meter dripline spacing, and 100% PGR rate consistently achieved higher lint yields and economic gains, highlighting potentials of adaptive deficit irrigation and PGR management in modern cotton cultivars to advance yield. The highest increase in lint yield was achieved 133 kg

N ha<sup>-1</sup> with diminishing returns at the highest rates of N applied. Results also shows varietal differences in yield responses, showing potential for statewide or regionwide adaptation across eco-zones, and emphasizing the need for selecting cotton cultivars suited to specific management practices (irrigated v's non-irrigated) systems. Future research should explore the long-term impacts of SDI on water-use efficiency, nitrogen dynamics, and variety stress tolerance with PGR applications. Additionally, further investigation into the physiological mechanisms underlying varietal responses to irrigation and PGR application could provide valuable insights to refine cotton variety selection. This research provides foundational data that can guide producers in optimizing their resources used for enhanced productivity and profitability in cotton production in the unique environmental conditions of the Southeast Coastal Plain.

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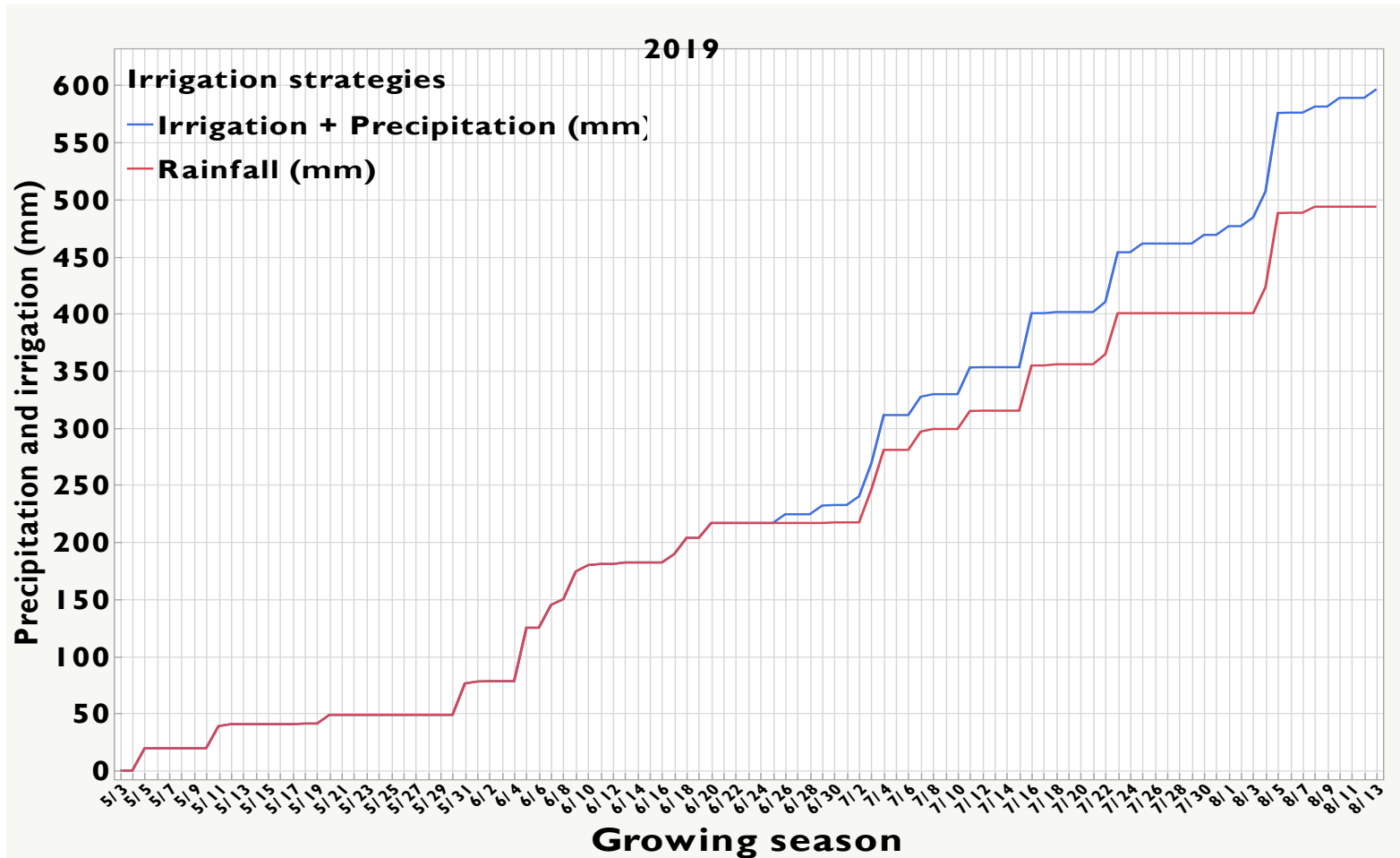


Figure 4.1: Bar and Line Graph Showing Weather (Temperatures And Rainfall) During the 2019 To 2021 Growing Seasons at Hare Road Suffolk

VA.

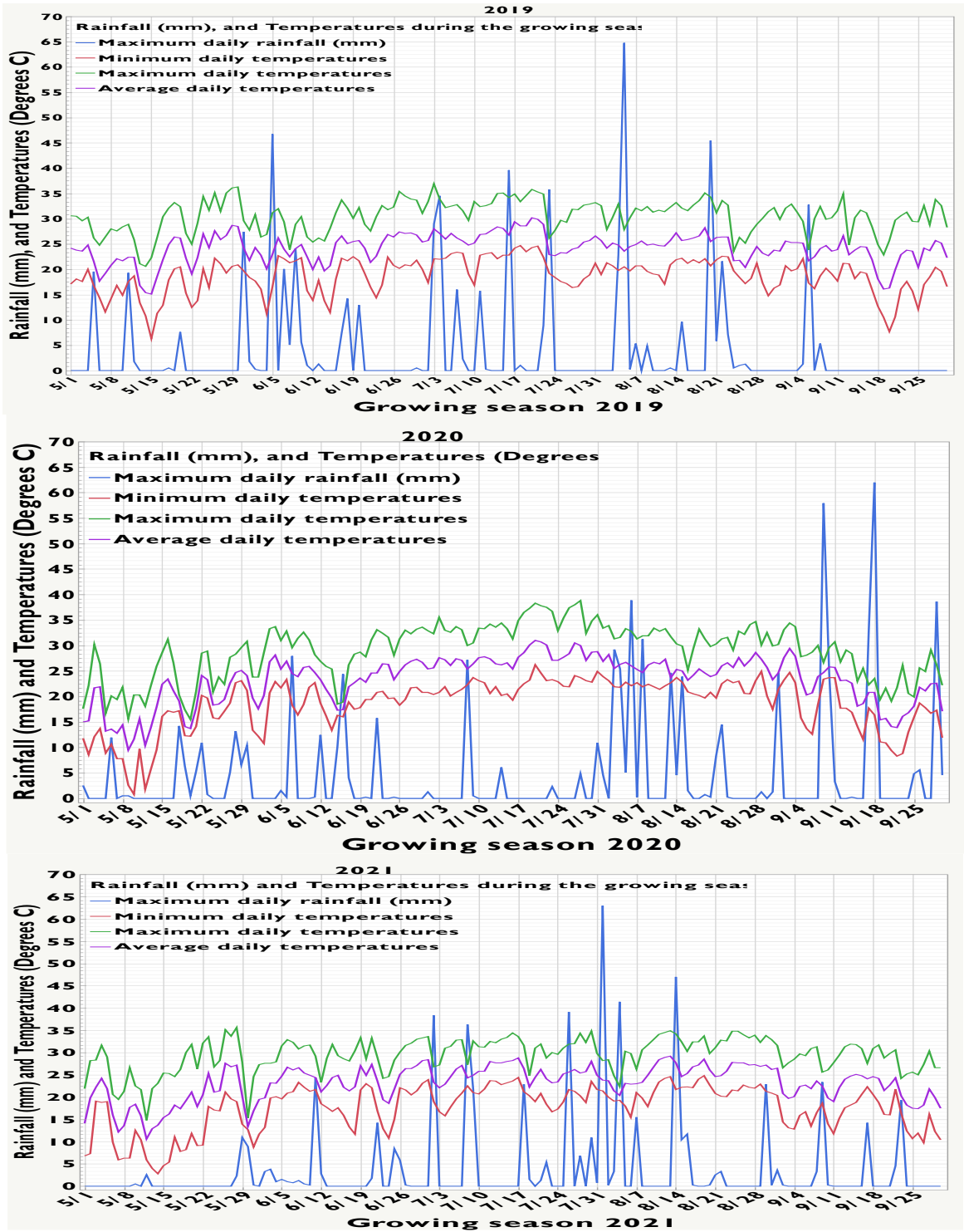
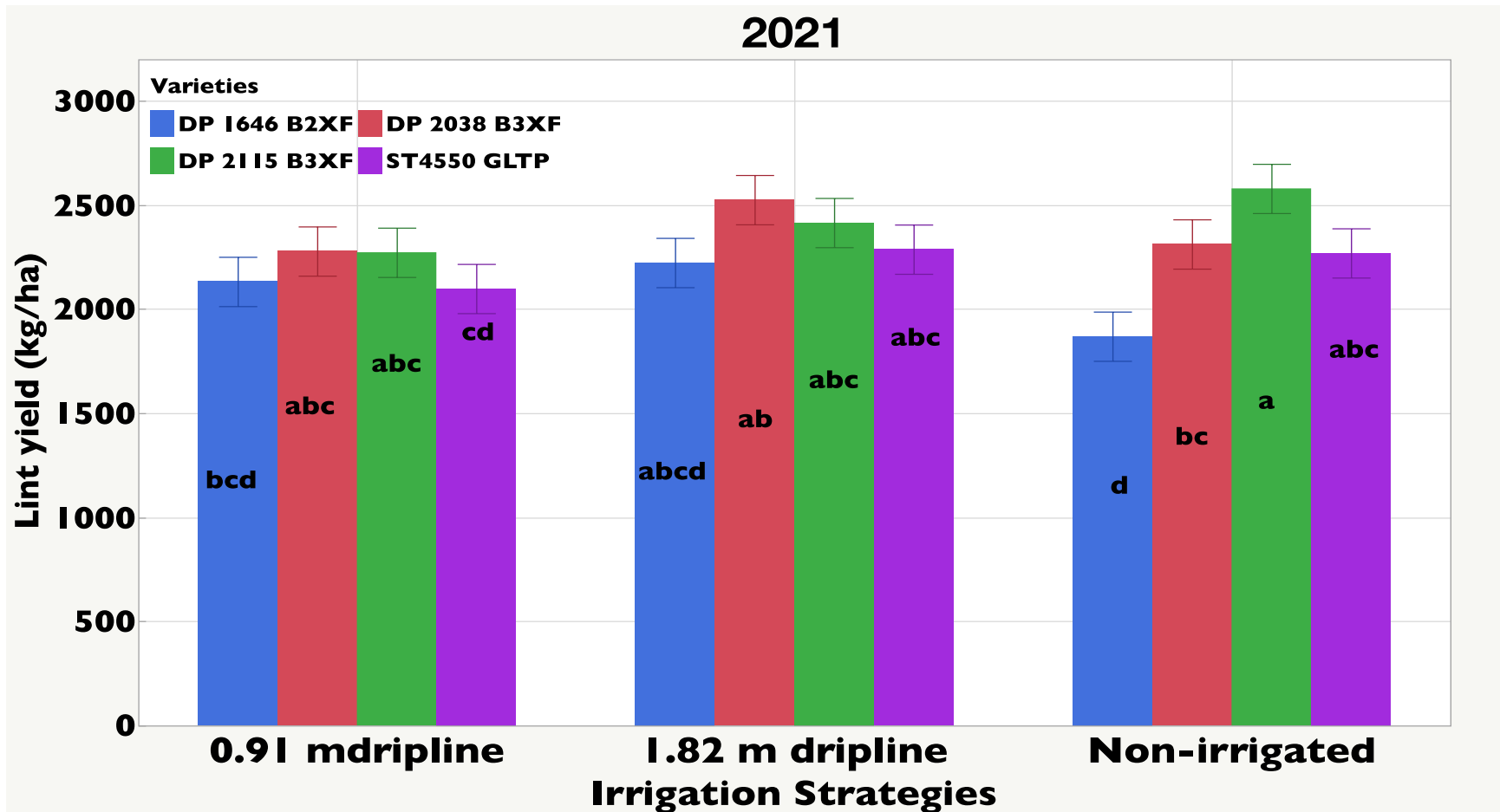
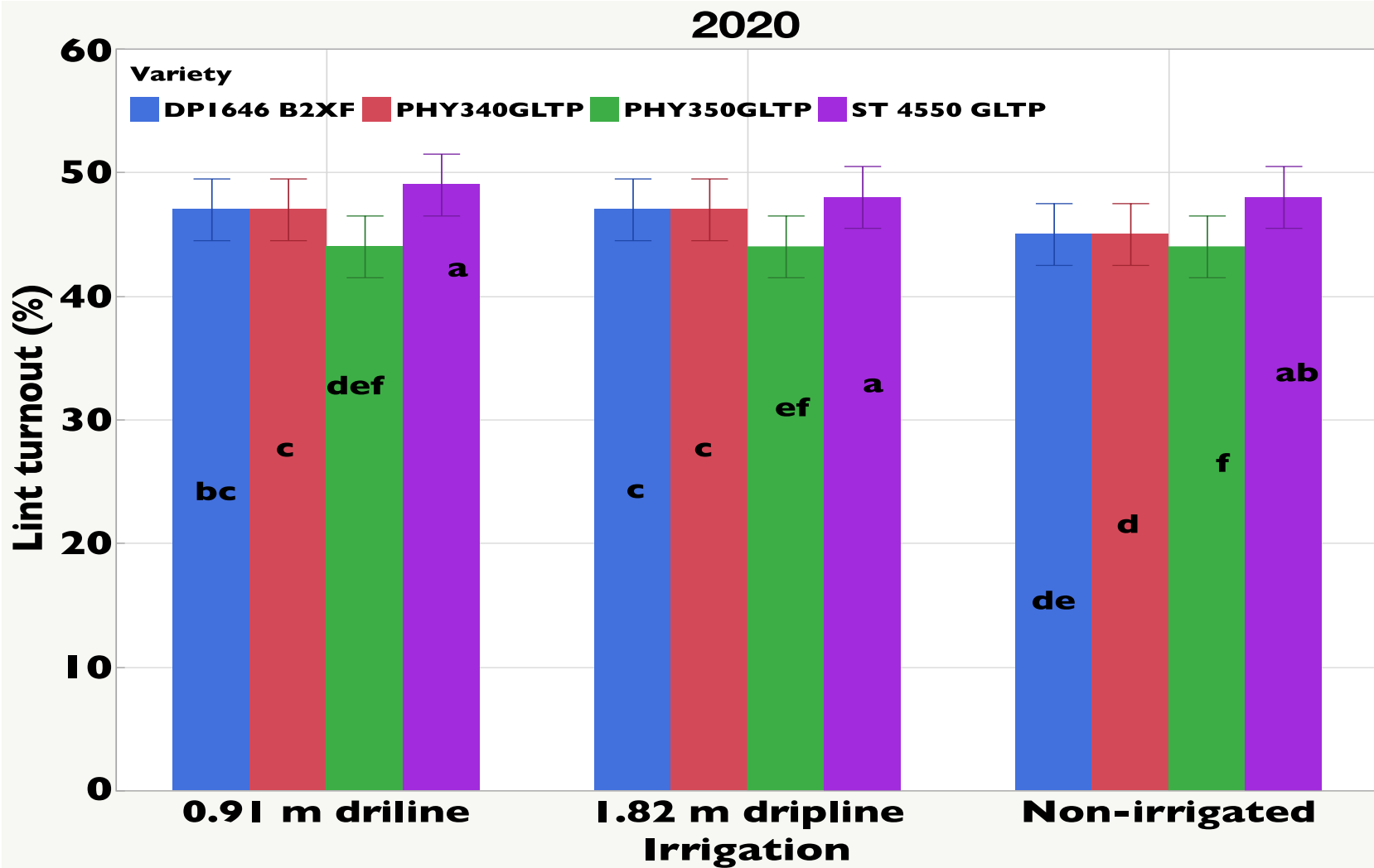


Figure 4.2: Bar and line graph showing weather (temperatures and rainfall) during the 2019 to 2021 growing seasons at Hare Road Suffolk VA.



**Figure 4.3:** Lint yield (kg/ha) of four cotton varieties under different dripline spacings in 2021 (Experiment 1). Bars represent the interaction between dripline spacing (0.91 m, 1.82 m, and non-irrigated) and cotton variety on lint yield. An asterisk (\*) indicate significant interaction effects at  $P < 0.1$ . Bars with the same color = same variety.



**Figure 4.4:** Interaction of dripline spacing and cotton variety on lint turnout percentage in 2020. Bars with the same letter represent same variety. An asterisk (\*) indicate significant interaction effects at  $P \leq 0.1$ . Narrower 0.91 m dripline spacing resulted in higher lint turnout compared to wider 1.82 m spacing, with variety ST4550GLTP performing best overall.

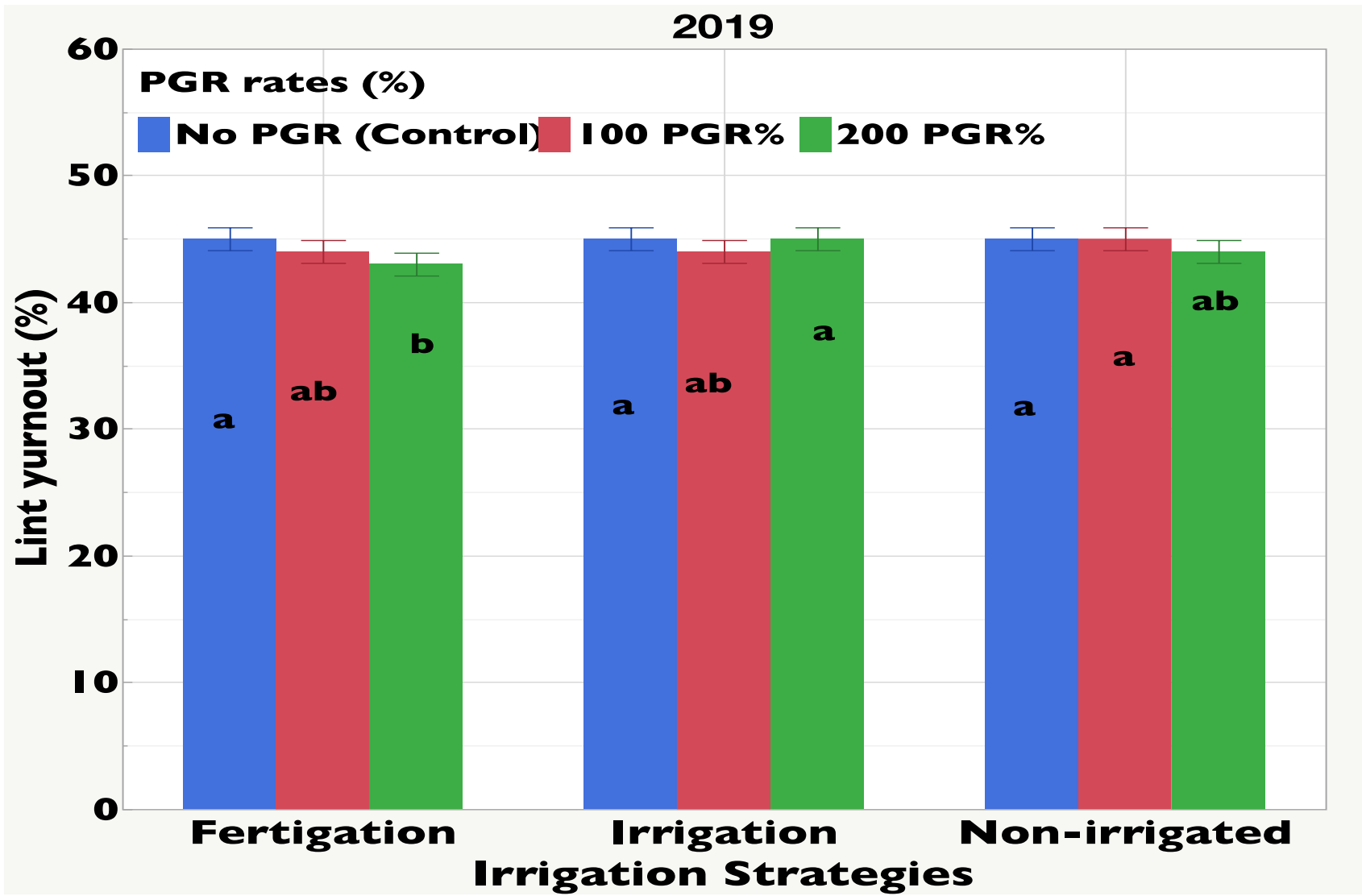
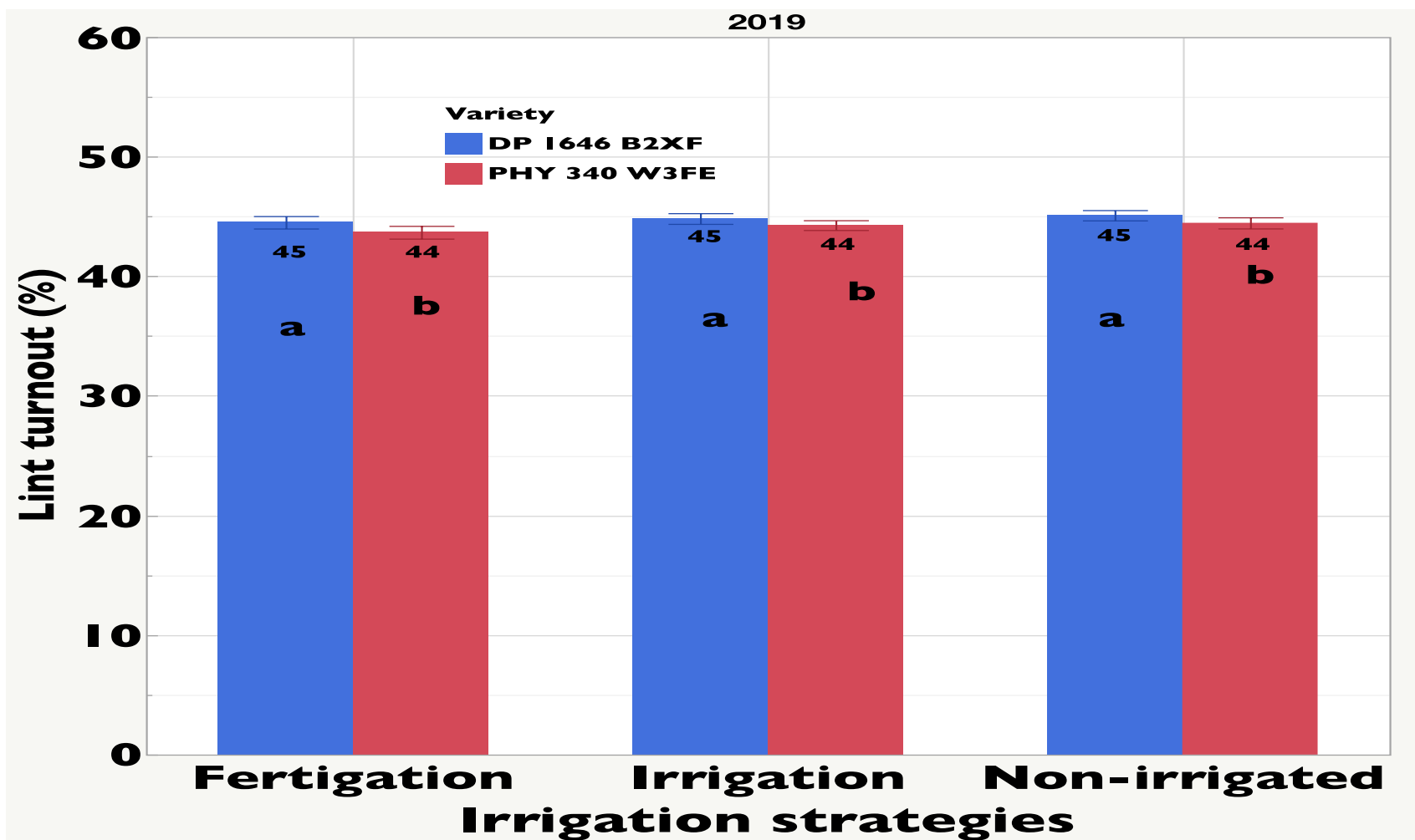


Figure 4.5: Bar graph illustrating the effect of PGR rates and irrigation interactions on percentage lint turnout in 2019 (Experiment 2).

Bars with the same color represent same PGR rate. An asterisk (\*) indicate significant interaction effects at  $P \leq 0.1$ .



**Figure 4.6:** Bar graph illustrating the effect of Variety and irrigation interactions on percentage lint turnout in 2019 (Experiment 2).

Bars with the same color represent same PGR rate. An asterisk (\*) indicate significant interaction effects at  $P \leq 0.1$ .

**Table 4.1:** Planting dates, PGR rates and Timing for the two experiments under the SDI system at TAREC (2019-2021)

<b>Agronomic Management</b>	<b>Experiment 1</b>			<b>Experiment 2</b>		
	<b>2019</b>	<b>2020</b>	<b>2021</b>	<b>2019</b>	<b>2020</b>	<b>2021</b>
<b>Planting date</b>	April 30 <sup>th</sup>	May 26 <sup>th</sup>	May 13 <sup>th</sup>	April 30 <sup>th</sup>	May 26 <sup>th</sup>	May 13 <sup>th</sup>
<b>1<sup>st</sup> PGR Application date</b>	June 24 <sup>th</sup>	July 14 <sup>th</sup>	July 22 <sup>nd</sup>	June 24 <sup>th</sup>	July 14 <sup>th</sup>	July 22 <sup>nd</sup>
	----- PGR Application Rate (ml ha <sup>-1</sup> ) -----					
<b>No PGR</b>	-	-	-	-	-	-
<b>100%</b>	729	729	729	729	729	729
<b>150%</b>	1,093	1,093	1,093	1,093	1,093	1,093
<b>200%</b>	1,457	1,457	1,457	1,457	1,457	1,457
<b>2<sup>nd</sup> PGR Application date</b>	July 25 <sup>th</sup>	July 28 <sup>th</sup>	August 12 <sup>th</sup>	July 25 <sup>th</sup>	July 28 <sup>th</sup>	August 12 <sup>th</sup>
	----- PGR Application Rate (ml ha <sup>-1</sup> ) -----					
<b>No PGR</b>	-	-	-	-	-	-
<b>100%</b>	874	874	874	874	874	874
<b>150%</b>	1,312	1,312	1,312	1,312	1,312	1,312
<b>200%</b>	1,749	1,749	1,749	1,749	1,749	1,749

**Table 4.2:** Mehlich-1 Soil Chemical Properties at Experimental Sites under Subsurface Drip Irrigation in Suffolk, VA (2019-2021).

Experiment	Mehlich I Extractable Nutrients									
	Phosphorous (P)	Potassium (K)	Calcium (Ca)	Magnesium (Mg)	Zinc (Zn)	Manganese (Mn)	Copper (Cu)	Iron (Fe)	pH <sup>‡</sup>	Est CEC <sup>†</sup>
	.....kg ha <sup>-1</sup> .....				..... mg kg <sup>-1</sup> .....			1:01	meq/100g	
	-----2019-----									
1 <sup>st</sup> study	87	250	1038	117	0.6	5.4	0.2	10.6	6.9	3.1
2 <sup>nd</sup> study	82	271	1275	141	0.5	6.9	0.2	11.2	7.1	3.7
	-----2020-----									
1 <sup>st</sup> study	84	180	1075	138	0.6	4.5	0.2	14.2	6.8	1.3
2 <sup>nd</sup> study	84	167	955	122	0.6	4.1	0.2	14.5	6.7	2.8
	-----2021-----									
1 <sup>st</sup> study	73	129	788	103	0.9	2.6	0.1	10.6	5.9	2.6
2 <sup>nd</sup> study	70	126	863	108	0.9	2.8	0.1	10.6	6.1	2.6

<sup>‡</sup>Soil pH measured using 1:1 of soil to water.

<sup>†</sup>Cation exchange capacity

**Table 4.3:** Effects of dripline spacing, PGR rates (%), and cotton varieties on seed, lint yield, and turnout, for experiment 1

Main effects	2019		2020		2021	
	Lint yield	Lint turnout	Lint yield	Lint turnout	Lint yield	Lint turnout
	kg ha <sup>-1</sup>	g lint g <sup>-1</sup> seed cotton	kg ha <sup>-1</sup>	g lint g <sup>-1</sup> seed cotton	kg ha <sup>-1</sup>	g lint g <sup>-1</sup> seed cotton
<b>Dripline spacing (m) (a)</b>						
Non-irrigated	1988	0.45	1370 b*	0.45 b	2258 ab	0.53
0.91 m	1973	0.46	1608 a	0.48 a	2196 b	0.53
1.82 m	2023	0.45	1543 a	0.47 a	2364 a	0.53
<b>P-value</b>	<b>ns<sup>†</sup></b>	<b>ns</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>0.019</b>	<b>ns</b>
<b>PGR rates (%) (b)</b>						
no PGR	1962	0.46 a*	1483	0.47 a	2188 b	0.54 a
100%	2039	0.45 b	1538	0.46 b	2377 a	0.53 b
150%	2025	0.45 ab	1523	0.46 b	2288 ab	0.53b
200%	1961	0.45 b	1486	0.46 b	2237 b	0.53 b
<b>P-value</b>	<b>ns</b>	<b>0.052</b>	<b>ns</b>	<b>&lt;0.001</b>	<b>0.043</b>	<b>&lt;0.001</b>
<b>Varieties (c)</b>						
DP1646 B2XF	1967 ab	0.46 b	1503 b	0.46 b	2076 c	0.52 c
DP2115 B3XF	-	-	-	-	2423 a	0.52 bc
DP2038 B3XF	-	-	-	-	2373 a	0.55 a
ST 4550 GLTP	2127 a	0.47 a	1680 a	0.48a	2219 b	0.52 b
PHY340GLTP	1960 b	0.456b	1462 bc	0.46 b	-	-
PHY350GLTP	-	-	1385 c	0.44 c	-	-
ST5020GLTP	1933 b	0.43 c	-	-	-	-
<b>P-value</b>	<b>0.082</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>0.002</b>
<b>Interactions</b>						
a*b	ns	ns	ns	ns	ns	ns
a*c	ns	ns	ns	0.047	0.016	ns
b*c	ns	ns	ns	ns	ns	ns

\*Means with the same letter within columns are not significantly different at PrF ≤ 0.1.

<sup>†</sup> ns indicates overall ANOVA was not significant at PrF ≤ 0.1.

**Table 4.4:** Economic Impact of Dripline Spacing and Plant Growth Regulators on Lint Yield for Cumulative 3-years (2019-2021)

	2019 Revenues	2020 Revenues	2021 Revenues	3-year average impact <sup>‡</sup>
	.....Dollars ha <sup>-1</sup> .....			
<b>Dripline spacing</b>				
Non-irrigated	3,002	2,069 b*	3,410 ab	
0.91 m dripline	2,979	2,428 a	3,316 b	\$81
1.82 m dripline	3,055	2,330 a	3,570 a	\$158
P-value	<b>ns</b>	<b>&lt;0.001</b>	<b>0.019</b>	
PGR rates (%)				
no PGR	2,963	2,239	3,304 b	
100% PGR	3,079	2,322	3,589 a	\$162
150% PGR	3,058	2,300	3,455 ab	\$102
200% PGR	2,961	2,244	3,378 ab	\$26
P-value	<b>ns</b>	<b>ns</b>	<b>0.008</b>	

\*Means with the same letter within columns are not significantly different at PrF ≤ 0.1.

† **ns** indicates overall ANOVA was not significant at PrF ≤ 0.1.

‡3-year average impact was calculated at \$1.51 kg<sup>-1</sup> of lint

**Table 4.5:** Effects of fertigation, PGR rates (%), nitrogen rates, and upland cotton varieties on lint yield and turnout, 2019-2021 in experiment 2

Main effects	2019		2020		2021	
	Lint yield kg ha <sup>-1</sup>	Lint turnout % <sup>1</sup>	Lint yield kg ha <sup>-1</sup>	Lint turnout % <sup>1</sup>	Lint yield kg ha <sup>-1</sup>	Lint turnout % <sup>1</sup>
<b>Irrigation (a)</b>						
Irrigation	1668 a	0.45	1448 a*	0.45 a	1468 b	0.46 a
Non-irrigated	1596 ab	0.45	1274 b	0.43 b	1650 a	0.45 b
Fertigation	1530 b	0.44	1428 a	0.45 a	1464 b	0.45 ab
<b>P-Value</b>	<b>0.041</b>	<b>ns</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>0.021</b>
<b>PGR rates (b)</b>						
no PGR	1636 a	0.45 a	1390	0.45 a	1577 a	0.46 a
100% PGR	1639 a	0.44 ab	1356	0.44 ab	1561 a	0.45 b
200% PGR	1519 b	0.44 b	1405	0.44 b	1444 b	0.45 c
<b>P-Value</b>	<b>0.043</b>	<b>0.026</b>	<b>ns</b>	<b>0.002</b>	<b>0.024</b>	<b>&lt;0.001</b>
<b>N rates (kg ha<sup>-1</sup>) (c)</b>						
87kg	1481 b	0.44	1357	0.44 a	1387 b	0.47
133kg	1614 a	0.45	1409	0.44 ab	1604 a	0.45
178kg	1699 a	0.44	1384	0.44 b	1592 a	0.45
<b>P-Value</b>	<b>0.001</b>	<b>ns</b>	<b>ns</b>	<b>0.020</b>	<b>&lt;0.001</b>	<b>ns</b>
<b>Variety (d)</b>						
DP1646B2XF	1618	0.45 a	1475 a	0.44	1477 b	0.44 b
PHY340W3FE	1578	0.44 b	1293 b	0.44	-	-
ST4550GLTP	-	-	-	-	1578 a	0.46 a
<b>P-Value</b>	<b>ns</b>	<b>0.072</b>	<b>&lt;0.001</b>	<b>ns</b>	<b>0.019</b>	<b>&lt;0.001</b>
<b>Interactions</b>						
a*b	ns	0.035	ns	ns	ns	ns
a*c	ns	ns	ns	ns	ns	ns
a*d	ns	0.029	ns	ns	ns	ns
b*c	ns	ns	ns	ns	0.094	ns
b*d	ns	ns	ns	ns	ns	0.022

b*c*d	ns	ns	ns	ns	ns	ns
a*b*c*d	ns	ns	ns	ns	ns	ns

Acronyms: % lint turnout = g lint g seed cotton<sup>-1</sup>. \*Means with the same letter within columns are not significantly different at PrF ≤ 0.1. † ns indicates overall ANOVA was not significant at PrF ≤ 0.1

**Table 4.6:** Economic Benefits of Irrigation, Fertigation, and Plant Growth Regulator Rates on 3-Year Average Lint Yield (2019-2021)

Irrigation Strategies	2019	2020	2021	Ç3-year average impact
	Revenue	Revenue	Revenue	
	.....Dollars ha <sup>-1</sup> .....			
<b>Irrigation strategies</b>				
Non-irrigated	2,410 ab	1,924 b	2,492 a*	
Irrigation	2,519 a	2,186 a	2,217 b	\$32
Fertigation	2,310 b	2,156 a	2,211 b	\$-49
<b>P-value</b>	<b>0.041</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	
<b>PGR rates (%)</b>				
no PGR	2,470 a	2,099	2,381 a	
100%	2,475 a	2,048	2,357 a	\$-23
200%	2,294 b	2,122	2,180 b	\$-118
<b>P-value</b>	<b>0.043</b>	<b>ns</b>	<b>0.024</b>	

Acronyms: \$ROI=Return on investment.

\*Means with the same letter within columns are not significantly different at PrF ≤ 0.1.

† ns indicates overall ANOVA was not significant at PrF ≤ 0.1.

Ç3-year average impact was calculated from 3-year average price of \$1.51 kg<sup>-1</sup> of lint

## **5.0 General Conclusion**

### **Optimizing Corn and Cotton Performance with Adaptive Management Systems and Subsurface Drip Irrigation in the Mid-Atlantic USA**

The initial study demonstrated the benefits of integrating in-season nutrient application, biostimulants, foliar fungicides in sustaining yield. The responses of these practices varied from site to site, and management levels, demonstrating potential for site specific management to advance yield. Notably, there was a significant improvement in grain yields in non-irrigated conditions with intensive management, and no big difference in yield among standard management and standard check under irrigation demonstrating the opportunities for farmers to increase yield with irrigation. In most times, the yields of the irrigated standard management practices were higher than those of irrigated intensive management showcasing the potential of advancing yield with irrigation in the farmer standard management. It was revealed that irrigation emerged as a pivotal factor, contributing to corn grain yield increase by 8.9 and 34% in the intensive and standard management practices. Future research should focus to refine these treatments that showed promise for yield increase across multiple locations.

In the second study, irrigation, nitrogen management, and seeding rate strategies in Corn were studied, and interesting facts revealed. The subsurface drip irrigation (SDI) dripline of 0.91, the 0.91 meter dripline equipped with volumetric water content (VWC) sensors and 0.91 meter dripline with fertigation, emerged as the most effective SDI strategies yielding substantial economic returns of \$985, \$886, and \$816 per hectare in gross revenue compared to non-irrigated systems. Furthermore, the application of the 0.91-meter dripline with soil volumetric content (SVC) demonstrated slightly reduced water usage relative to the 0.91-meter dripline but

produced comparable results, indicating the promise for sustainable water resource utilization while advancing yield using sensors in automating irrigation. The 0.91 meter with fertigation illustrated the advantages of precision nutrient delivery alongside irrigation. The interplay between irrigation and nitrogen application rates illustrates significant challenges in nitrogen management under comparable traditional agronomic conditions, highlighting opportunities for optimizing nitrogen utilization in Virginia. Achieving greater yields with lower nitrogen rates through irrigation underscores the observation that some nitrogen resources have not been fully exploited under arid conditions. The results indicate that the efficiency of agronomic inputs including seeding and fertilizers (especially N) can be enhanced through strategic irrigation practices. Notably, the interactions among irrigation, nitrogen rates, and seeding density further underscore the necessity for meticulous management approaches. The irrigation increased yield at all nitrogen rates reaching the highest increase at nitrogen rate of 267 kg ha<sup>-1</sup> and seeding rate of 88,920 plants ha<sup>-1</sup> represents a viable strategy for improving yield and economic viability in corn. Additionally, all the irrigation strategies tested produced 56% more grain than non-irrigated and had over 100% more yield compared to the Virginia's State average corn grain yield, showcasing the opportunity to increase yield and profitability of corn in Virginia with irrigation. Overall, irrigation emerged as a pivotal factor driving yield enhancements, signaling promising prospects for agronomic profitability in corn within Virginia and the mid-Atlantic region. These findings suggest the potential to expand the yield potential of corn beyond historically established boundaries in Eastern Virginia.

The influence of irrigation strategies, and variety on lint yield was evident in five out of six studies conducted across two experiments. The variability in response among different varieties highlights the genetic diversity concerning stress tolerance and moisture requirements

necessary for optimal yield accumulation. This further shows that traditional variety selection should incorporate irrigation assessments to evaluate adaptability in diverse environmental conditions. While the narrower spacing of 0.91 meters drip irrigation improved yields in corn (study two), it yielded inconsistent results in cotton management, where its performance was comparable to both non-irrigated and irrigation with 1.82-meter dripline spacing, which ultimately produced higher yields. These observations suggest that cotton yields can be effectively enhanced through deficit irrigation strategies.

Cotton, varieties exhibited distinct responses to irrigation techniques and plant growth regulator (PGR) applications. The most favorable yields were achieved using a 1.82-meter dripline spacing as well as the 100% PGR application rate, resulting in lint profits ranging from \$158 to \$162 per hectare over non-irrigated. The best nitrogen application rate was 133 kg N ha<sup>-1</sup> with lower return on investment likely at higher N rates (178 kg N ha<sup>-1</sup>), which was consistent with previous studies on cotton N rate refinement, potentially enhancing profitability and sustainability of cotton. Most of the tested strategies averaged over 60+ more percent lint yield than the Virginia long term average yield, indicating a potential to surpass the national average yield which could generate over \$4.5 millions more revenue to the Virginia cotton growers. These findings show the importance of adaptive deficit irrigation, site-specific management, and integration of strategies to improve profitability of cotton systems in the southeastern coastal plains of Virginia.

Future research should assess the effects of Adaptive Crop Management (ACM) practices on soil health, water use efficiency, and systemic resilience. Conducting studies on irrigation practices within farmers' fields is critical for facilitating practical learning among producers. Comprehensive cost-benefit analyses are necessary to evaluate the economic viability of

advanced irrigation systems across various farm scales and socio-economic contexts, thereby promoting the adoption of innovative methodologies. Moreover, the integration of genotypic characterization of crop varieties with precision irrigation and plant growth regulator (PGR) applications, alongside nitrogen management, could enhance the efficacy of variety selection. Additionally, exploring the potential of remote sensing technologies, machine learning algorithms, and decision support systems will be instrumental in refining site-specific management strategies.