



## Article

# Early and Late Season Nutrient Stress Conditions: Impact on Cotton Productivity and Quality

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**Abstract:** Modern cotton (*Gossypium* spp. L) cultivars are efficient in nutrient uptake and utilization, and thus, may potentially tolerate nutrient stress. Early- and late-season nutrient stress (E-stress and L-stress, respectively) effects on cotton productivity and quality were assessed under different production conditions in Camilla and Midville, GA, USA. The E-stress received no nutrient application in the early season, but the full rates were split-applied equally at the initiation of squares and the second week of bloom stages. The L-stress received 30–40% of the full nutrient rates only at the initial stage of planting. The effects of nutrient stress on cotton productivity and fiber quality were not consistent across the different production conditions. Compared to the full nutrient rate, the E-stress did not adversely impact cotton yield, but rather it improved the lint and cottonseed yields under one production condition by 17.5% and 19.3%, respectively. Averaged across all production conditions, the L-stress decreased the lint and cottonseed yields by 34.4% and 36.2%, respectively. The minimal effects of E-stress on cotton suggest nutrient rates at the early season could be reduced and more tailored rates, informed by soil and plant tissue analyses, applied shortly before the reproductive phase.

**Keywords:** nutrient stress; cotton production; modern cultivars; biomass accumulation; fiber quality



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## 1. Introduction

Cotton (*Gossypium* spp. L) is a valuable industrial crop that contributes substantially to the agricultural economy of many countries. The Food and Agriculture Organization of the United Nations estimated the world's seed cotton (unginned cotton) production in 2020 to be 83.1 million tons, which was valued at \$52 billion [1]. The USA ranks third in cotton production in the world, behind China and India. In 2021, about 4.54 million ha of cotton was planted in the USA, and the top three leading producing states were Texas, Georgia, and Arkansas in descending order [2]. Lint and cottonseed are the two valuable industrial products of cotton, with lint being more valuable. In 2021, lint and cottonseed production value in the USA was \$7.46 billion and \$1.32 billion, respectively. Thus, cotton production management is mainly geared towards enhancing the productivity and quality of lint.

The average cotton lint yield in the USA has increased by 25.6% in the past 30 years, with a yield of 0.73 Mg ha<sup>−1</sup> in 1991 and 0.92 Mg ha<sup>−1</sup> in 2021 [2]. The increase in cotton lint yield can largely be attributable to improved agronomic practices and better performance of modern cultivars [3–5]. Rochester and Constable [6] compared cotton cultivars released in 2006 with those released in 1973. The authors observed a 40% increase in lint yield in the 2006 cultivars. In addition, the N, P, and K use efficiencies of the 2006 cultivars increased by 20%, 23%, and 24%, respectively, when compared to those of the 1973 cultivars [6]. In a

two-year field study in New Deal, TX, the average lint yields of cotton cultivar PM HS26 (released in 1990), FM 958 (released in 2000), and DP 1646 (released in 2016) were reported to be 1.11 Mg ha<sup>-1</sup>, 1.26 Mg ha<sup>-1</sup>, and 1.34 Mg ha<sup>-1</sup>, respectively [7]. The authors also observed that the 2016 and 2000 cultivars efficiently partitioned and remobilized essential nutrients more than the 1990 cultivar.

The efficient utilization of nutrients by modern cultivars could potentially confer better tolerance to nutrient stress, which would be desirable. There has been instability in the supply and prices of fertilizers over the past couple of years, with most fertilizers exceeding record prices in 2008. Lessons from the 2008 volatility in fertilizer prices suggest that farmers may not be willing to buy the usual tonnage of fertilizers at high price levels [8]. It is therefore important to determine the impact of reduced fertilizer application rates on the productivity and quality of modern cotton varieties. The high fertilizer prices in 2008 may have contributed to the reduced cotton lint yield in succeeding years. The average cotton lint yield in the USA in 2007 was 0.88 Mg ha<sup>-1</sup>, but it dropped to 0.81 Mg ha<sup>-1</sup> and 0.78 Mg ha<sup>-1</sup>, respectively, in 2008 and 2009 [2].

While low fertilizer application could impact cotton productivity, supplying more nutrients than needed could have adverse implications on the environment, such as acidification of soils, eutrophication in aquatic systems, and ozone layer depletion [9,10]. Nutrient uptake and partition studies show that nutrient requirement in cotton is minimal at the vegetative stage and then increases rapidly at the reproductive stage [7,11,12]. Synchronizing nutrient availability with crop demand could potentially increase nutrient use efficiency and reduce nutrient loss through ammonia volatilization, denitrification, runoff, and leaching [13–15]. However, standard nutrient management guidelines suggest the application of all recommended fertilizer rates before or at the initial stages of planting, except for N which is often split-applied. The minimal vegetation cover, coupled with high rainfall and temperature conditions, make fertilizers applied in the early season susceptible to losses.

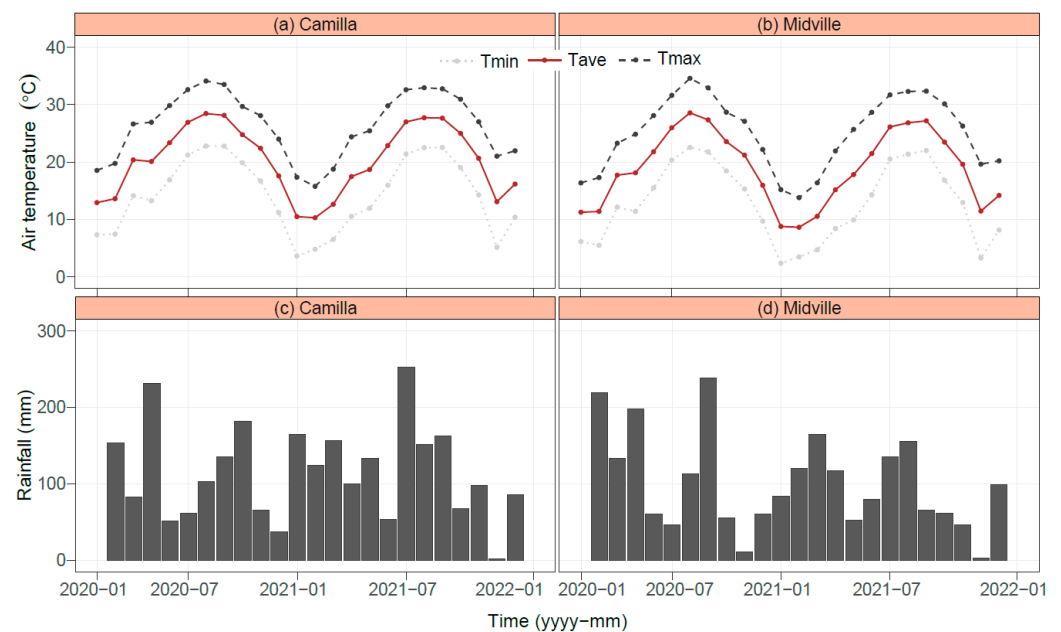
Determining the response of modern cotton cultivars to no fertilizer application during the early season growth could inform adaptive nutrient management strategies. Residual nutrients in the soil and crop residues could meet the nutritional demand for cotton at the early season growth stage [16–18]. The objective of this study was therefore to assess the impact on the productivity and quality of modern cotton varieties to varying degrees of nutrient stresses under different production conditions.

## 2. Materials and Methods

### 2.1. Experimental Site

The research was conducted at the University of Georgia Stripling Irrigation Research Park in Camilla, GA (31°16′45.86″ N, 84°17′29.65″ W) and the Southeast Georgia Research and Education Center in Midville, GA (32°52′54.72″ N, 82°12′54.07″ W). Both sites have a humid subtropical climate, with annual average daily minimum, mean, and maximum air temperatures of 12.8 °C, 19.4 °C, and 26.0 °C, respectively, in Camilla and 11.3 °C, 18.0 °C, and 24.6 °C, respectively, in Midville [19]. The average annual precipitation in Camilla is 1314 mm, with 98 average rainy days, and the average annual precipitation in Midville is 1146 mm, with 102 average rainy days [19].

Air temperature over the two years of the study followed a similar pattern across the two locations, but it was relatively warmer in Camilla compared to Midville, with the average minimum, mean, and maximum air temperatures of 13.7 °C, 19.9 °C, and 26.1 °C, respectively, in Camilla, and 12.4 °C, 18.5 °C, and 24.6 °C, respectively, in Midville (Figure 1). In addition, rainfall received was relatively greater in Camilla, with an annual rainfall of 1378 mm in 2020 and 1384 mm in 2021. Annual rainfall in Midville was 1318 mm in 2020 and 1099 in 2021. Rainfall received between the planting and harvest of cotton was 547 mm and 776 mm in 2020 and 2021, respectively, in Camilla, and 482 mm and 532 mm, respectively, in 2020 and 2021 in Midville.



**Figure 1.** (a,b) Monthly minimum (Tmin), mean (Tave), and maximum (Tmax) air temperature, as well as (c,d) monthly total precipitation in Camilla and Midville, GA from 1 January 2020 to 31 December 2021.

The experimental field in Camilla had a Lucy loamy sand, classified as Loamy, kaolinitic, thermic Arenic Kandiudults, whereas the field in Midville had a Dothan loamy sand, classified as fine-loamy, kaolinitic, thermic Plinthic Kandiudults [20]. The average sand, silt, and clay content at the top 15 cm depth of the experimental field soils were 90.7%, 3.2%, and 6.1%, respectively, in Camilla, and 90.9%, 5.1%, and 4.0%, respectively, in Midville. In addition, the average soil pH and organic matter within 0–15 cm depth were 6.51 and 2.90 g kg<sup>−1</sup> in Camilla, respectively, and 6.40 and 4.67 g kg<sup>−1</sup> in Midville, respectively.

## 2.2. Field Experiment

Field experiments were established in 2020 and 2021 to evaluate early- and late-season nutrient stress (E-stress and L-stress) effects on cotton productivity and quality under different production conditions at the two locations. A reduced nutrient stress condition (R-stress) and standard fertility constituted the control treatments. In Camilla, the experiment was established under sub-surface drip irrigation (SSDI) systems in 2020 and 2021, and under an overhead irrigation system in only 2021. In Midville, the experiment was established under rainfed conditions in 2020 and 2021, and under an overhead irrigation system in only 2021, constituting six production conditions across the two locations. The two production conditions at both locations in 2021 were on separate fields (~100 m apart in Camilla and ~300 m apart in Midville). The four treatments were assessed under each production condition, except for the Midville 2020 rainfed condition where the standard fertility was not assessed.

The standard fertility treatment referred to nutrient recommendations (Table 1) by the University of Georgia Agricultural and Environmental Services Laboratories to make 1681 kg ha<sup>−1</sup> lint yield under irrigated conditions and 1121 kg ha<sup>−1</sup> lint yield under rainfed conditions [21]. The rates were based on the initial soil nutrient status of the experimental fields (Table 2). Nutrients reported as essential for cotton are N, P, K, Ca, Mg, S, Fe, Mn, Zn, B, and Cu [22]. To ensure minimal nutrient stress, the application of some rates of all the essential nutrients was made to the R-stress plots (Table 1). In Camilla, the R-stress plots received 30% of the full nutrient rates at the early stage of planting, another 30% each at square initiation and the second week of bloom (2-WoB) stages, and the remaining 10% at

the 6-WoB stage. In Midville, the R-stress plots received 40% of the full nutrient rates at the early stage of planting, and 30% each at square initiation and the 2-WoB stages.

**Table 1.** Full nutrient application rates (in kg ha<sup>−1</sup>) for the standard recommendation and reduced nutrient stress (R-stress) treatments imposed in Camilla and Midville, GA, under different production conditions.

| Nutrient Elements             | SSDI (2020) |          | Camilla SSDI (2021) |          | Overhead (2021) |          | Rainfed (2020) | Midville Rainfed (2021) |          | Overhead (2021) |          |
|-------------------------------|-------------|----------|---------------------|----------|-----------------|----------|----------------|-------------------------|----------|-----------------|----------|
|                               | Standard    | R-Stress | Standard            | R-Stress | Standard        | R-Stress |                | Standard                | R-Stress | Standard        | R-Stress |
| N                             | 84.1        | 118      | 106                 | 84.1     | 118             | 106      | 67.3           | 50.4                    | 78.5     | 84.1            | 118      |
| P <sub>2</sub> O <sub>5</sub> | 0.00        | 101      | 44.8                | 0.00     | 101             | 44.8     | 56.0           | 33.6                    | 67.3     | 78.5            | 101      |
| K <sub>2</sub> O              | 112         | 168      | 101                 | 112      | 168             | 101      | 112            | 33.6                    | 84.1     | 135             | 140      |
| Mg                            | 0.00        | 33.6     | 0.00                | 0.00     | 33.6            | 0.00     | 28.0           | 0.00                    | 5.60     | 0.00            | 5.60     |
| Ca                            | 0.00        | 5.60     | 0.00                | 0.00     | 5.60            | 0.00     | 5.60           | 0.00                    | 11.2     | 0.00            | 22.4     |
| S                             | 11.2        | 22.4     | 11.2                | 11.2     | 22.4            | 11.2     | 11.2           | 11.2                    | 11.2     | 11.2            | 11.2     |
| B                             | 0.56        | 2.24     | 0.56                | 0.56     | 2.24            | 0.56     | 2.24           | 0.56                    | 0.56     | 0.56            | 1.12     |
| Zn                            | 0.00        | 2.24     | 0.00                | 0.00     | 2.24            | 0.00     | 2.24           | 0.00                    | 1.12     | 0.00            | 2.24     |
| Mn                            | 0.00        | 1.12     | 0.00                | 0.00     | 1.12            | 0.00     | 1.12           | 0.00                    | 2.24     | 11.2            | 5.60     |
| Fe                            | 0.00        | 1.12     | 0.00                | 0.00     | 1.12            | 0.00     | 0.56           | 0.00                    | 2.24     | 0.00            | 2.24     |
| Cu                            | 0.00        | 0.56     | 0.00                | 0.00     | 0.56            | 0.00     | 0.56           | 0.00                    | 0.56     | 0.00            | 0.56     |

SSDI: Sub-surface drip irrigation; R-Stress: reduced nutrient stress.

**Table 2.** Initial nutrient status of the experimental field soil in Camilla and Midville under different production conditions.

| Soil Depth      | N    | P    | K    | Mg   | Ca  | S<br>kg ha <sup>−1</sup> | B    | Zn   | Mn   | Fe   | Cu   |
|-----------------|------|------|------|------|-----|--------------------------|------|------|------|------|------|
| Camilla         |      |      |      |      |     |                          |      |      |      |      |      |
| SSDI (2020)     | 8.47 | 82.3 | 92.0 | 62.2 | 955 | 5.04                     | 0.22 | 4.6  | 28.2 | 36   | 0.9  |
| SSDI (2021)     | 2.69 | 81.6 | 107  | 127  | 907 | 28                       | 0.45 | 6.05 | 13.5 | 10.1 | 1.01 |
| Overhead (2021) | 0.90 | 49.3 | 58.8 | 95.0 | 762 | 28.1                     | 0.45 | 6.15 | 15.1 | 12.3 | 2.13 |
| Midville        |      |      |      |      |     |                          |      |      |      |      |      |
| Rainfed (2020)  | 3.49 | 75.7 | 81.6 | 67.7 | 971 | 32.4                     | 0.22 | 5.62 | 20.2 | 37.1 | 0.67 |
| Rainfed (2021)  | 2.73 | 68.4 | 184  | 166  | 864 | 37.9                     | 0.67 | 7.64 | 15.6 | 17.2 | 0.45 |
| Overhead (2021) | 6.97 | 51.6 | 71.2 | 91   | 716 | 31.2                     | 0.45 | 5.9  | 6.39 | 19.3 | 1.01 |

Soil samples were collected from 0–15 cm depth with a 2.86 cm diameter AMS soil recovery probe (AMS Inc., American Falls, ID, USA). N was measured as Nitrate-N after extraction with 2 M KCl solution, whereas P, K, Ca, Mg, S, Fe, Mn, Zn, B, and Cu were measured after Mehlich I extraction. SSDI: Sub-surface drip irrigation.

The E-stress at both locations was induced by not making any nutrient application until the initiation of squares, after which the full nutrient rates specified for the R-stress were split-applied equally at the initiation of squares and the 2-WoB stages. Thus, the E-stress received the same nutrient application rates as the R-stress. The L-stress in Camilla was induced by applying only 40% of the full nutrient rates specified for the R-stress at the early stage of planting, whereas the L-stress in Midville was induced by applying only 30% of the full nutrient rates specified for the R-stress at the early stage of planting. Table S1 lists the nutrient sources applied. Granular fertilizer sources were used at both locations, except the Camilla SSDI conditions where liquid fertilizer sources were applied via fertigation at the 2-WoB and 6-WoB stages. The treatments were laid out in a randomized complete block design with four replications and plot dimensions (width × length) of 5.5 m × 11.0 m for the Camilla SSDI condition, 7.3 m × 12.2 m for the Camilla overhead irrigation condition, and 7.3 m × 9.1 m for all conditions in Midville.

### 2.3. Plot Management

Previous cash crops were peanut (*Arachis hypogaea*) and corn (*Zea mays*) for the 2020 and 2021 seasons, respectively, in Camilla and peanut for all seasons in Midville. All sites were under cereal rye (*Secale cereale*) cover crop, and the fields were prepared by strip-tilling to 30.5–45.7 cm depth. Deltapine<sup>®</sup> cotton variety DP 1646 B2XF (released in 2016) was used in Camilla and Stoneville<sup>®</sup> cotton variety ST 4550 GLTP (released in 2019) was used in Midville, and they were planted at 107,639 seeds ha<sup>−1</sup> and 91.4 cm row spacing. The

SSDI system constituted a Netafim Typhoon drip tape (Netafim Irrigation, Inc., Fresno, CA, USA), with 46 cm emitter spacing and  $1.5 \text{ L h}^{-1}$  discharge rate, installed at the middle of every row (46 cm to the side of plant rows). The drip tapes at every other middle of the plant rows were used for irrigation in this study (one drip tape line serviced two plant rows), as per common grower practice. The overhead irrigation was a lateral irrigation system in Camilla and a center pivot irrigation system in Midville. Irrigation amounts were 200 mm (Camilla 2020 SSDI), 132 mm (Camilla 2021 SSDI), 184 mm (Camilla 2021 overhead), and 95.3 mm (Midville 2021 overhead), which depended on rainfall, location, and irrigation method. Weed and pest control and the use of growth regulators and defoliants followed standard recommendations by the University of Georgia Cooperative Extension [23,24].

#### 2.4. Data Collection

Initial soil nutrient levels within the top 15 cm depth were analyzed following standard protocols by Waters Agricultural Laboratories, Inc. The soil samples were collected with a 2.86 cm diameter AMS soil recovery probe (AMS Inc., American Falls, ID, USA). Nitrate-N was measured, after extraction in a 2 M KCl solution, with the automated flow injection analysis system (FIAlyzer-1000, FIALab Instruments, Inc., Seattle, WA, USA), and extractable P, K, Ca, Mg, S, Fe, Mn, Zn, B, and Cu were measured, after extraction in Mehlich I solution, with an inductively coupled plasma optical emission spectrophotometer (ICP-OES; iCAP<sup>TM</sup> 6000 Series, Thermo Fisher Scientific, Cambridge, United Kingdom).

Aboveground plant tissues were sampled at square initiation, 2-WoB, and 7-WoB stages, and shortly before harvest (after defoliation), except for the Midville location where samples were not collected at the 7-WoB stage. At every sampling stage, the aboveground biomass was collected from a 1 m strip of a non-harvest row, ensuring a minimum of 1 m buffer during subsequent sampling. The samples were oven-dried at  $78^\circ\text{C}$  to obtain constant weight, after which the weights were recorded and used to calculate biomass accumulation. Plant height, the number of main stem nodes per plant, the total number of bolls per plant, the number of harvestable bolls per plant, and seed cotton per boll were determined at physiological maturity from five plants selected randomly within non-harvest rows of each plot.

Harvesting was performed mechanically by sampling two entire rows of every plot with a cotton picker, and weights of the seed cotton were measured. Thereafter, the seed cotton samples were ginned at the University of Georgia Micro Gin in Tifton, GA to determine the gin turnout, which was used to calculate the lint and cottonseed yields. Fiber samples were transported to the USDA classing office in Macon, GA to measure fiber quality parameters, including fiber length, fiber strength, uniformity, micronaire, reflectance (RD), and yellowness (+b), following standard protocol [25].

#### 2.5. Statistical Analyses

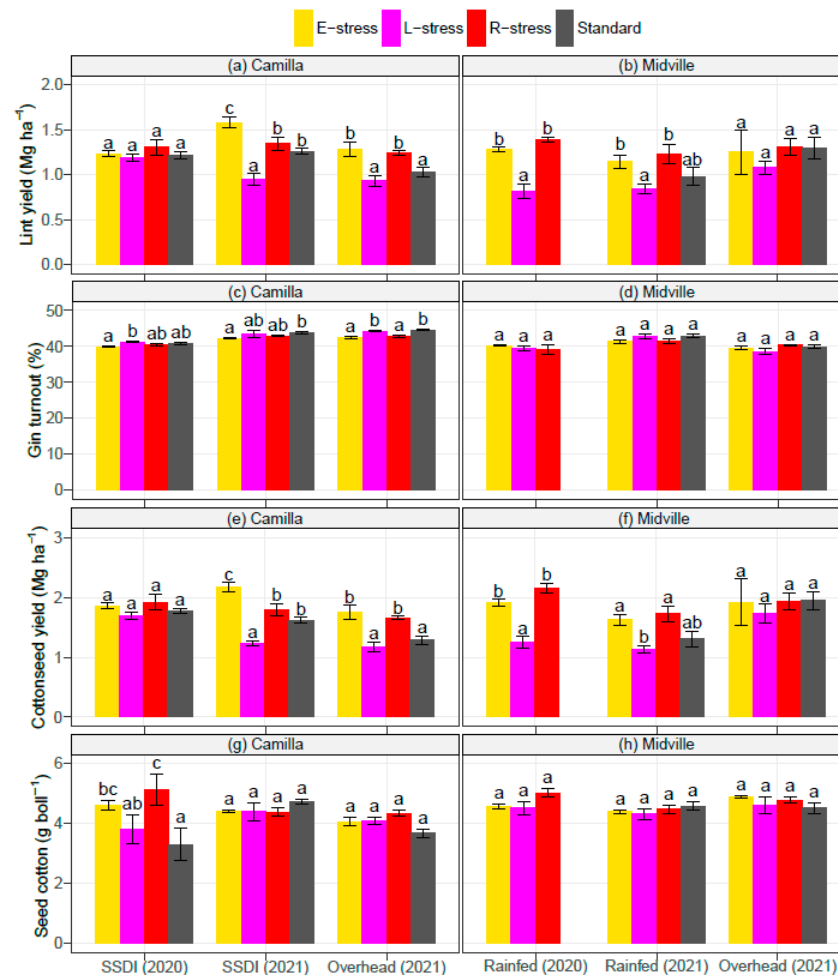
Separate statistical analyses were performed for each location because of differences in the level of nutrient stress imposed. Plant growth, yield, and fiber quality data, except for the biomass data, were analyzed with the linear mixed model using the “lme4” package in R [26]. The nutrient stress and production conditions were considered fixed effects and block was considered a random effect. The biomass data were analyzed as repeated measure analyses, also using the “lme4” package in R [26]. The sampling time was assigned as a within-plot factor variable, nutrient stress as between plot factor variable, and block as a random term.

Normality of residuals, homoscedasticity of variance, and sphericity assumptions were tested, and appropriate transformations (square root and Box–Cox transformation methods) and corrections (Greenhouse–Geisser and Huynh–Feldt correction methods) were applied as appropriate. Mean separations were performed using the least square means and the adjusted Tukey multiple comparison procedure with the ‘emmeans’ package in R [27]. The significance level for all analyses was assessed at  $p = 0.05$ .

### 3. Results

#### 3.1. Lint Yield, Gin Turnout, and Seed Cotton

The main effects of nutrient stress were significant on cotton lint yield, gin turnout, cottonseed yield, and the seed cotton weight per boll in Camilla, but the effects were only significant on lint yield and cottonseed yield in Midville (Table S2). In addition, the interaction effects of nutrient stress and production conditions were significant on lint yield, cottonseed yield, and seed cotton weight per boll in Camilla, but their effects were not significant on those variables in Midville. Compared to R-stress, the E-stress did not cause a significant reduction in lint yield, but rather, it significantly increased the lint yield by 17.5% under Camilla 2021 SSDI condition (Figure 2a,b). In contrast, the L-stress led to a significant reduction in lint yield in four production conditions when compared to the R-stress. The yield reductions were 41.7%, 33.3%, 69.4%, and 45.4%, respectively, under Camilla 2021 SSDI, Camilla 2021 overhead irrigation, Midville 2020 rainfed, and Midville 2021 rainfed conditions. Compared to R-stress, the standard fertility underperformed but the differences were not significant, except under Camilla 2021 overhead condition (20.6% lower lint yield). Averaged over all production conditions across the two locations, the lint yield was 1.29 Mg ha<sup>-1</sup>, 0.97 Mg ha<sup>-1</sup>, 1.30 Mg ha<sup>-1</sup>, and 1.15 Mg ha<sup>-1</sup> for the E-stress, L-stress, R-stress, and the standard fertility, respectively.



**Figure 2.** Nutrient stress effects on lint yield (a,b), gin turnout (c,d), cottonseed yield (e,f), and seed cotton yield per boll (g,h) in Camilla and Midville, GA under different production conditions. Within location and production conditions, means of nutrient stress treatments not sharing any letter are significantly different using the least squares means and adjusted Tukey multiple comparison procedure ( $p < 0.05$ ). Error bars indicate the standard error of the mean ( $n = 4$ ). SSDI: Sub-surface drip irrigation.

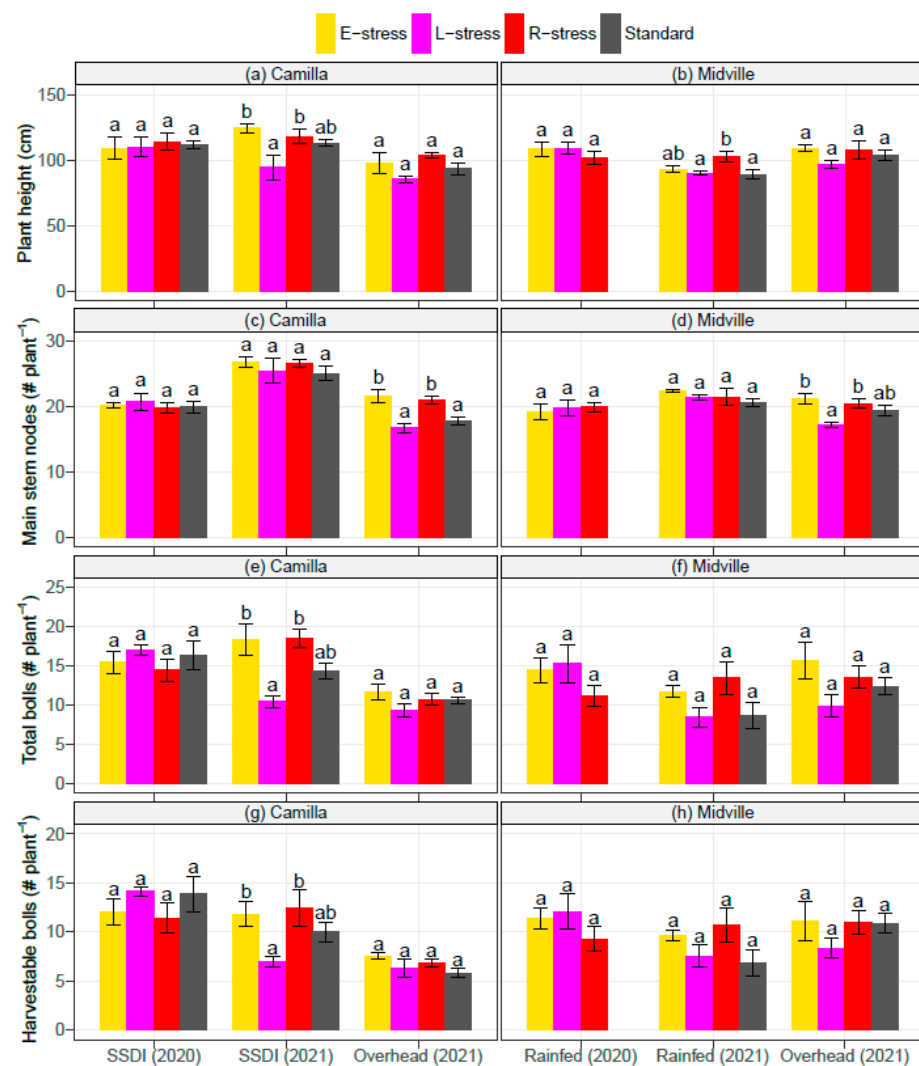
While the effects of nutrient stress on gin turnout were statistically significant under all production conditions in Camilla, the magnitude of the differences was small, with gin turnout ranging from 39.9% to 41.3% under Camilla 2020 SSDI, 42.2% to 43.7% under Camilla 2021 SSDI, and 42.3% to 44.5% under Camilla 2021 overhead irrigation (Figure 2c,d). Thus, the effects of nutrient stress on cottonseed yield (Figure 2e,f) followed the same trend as the effects on lint yield. Averaged over all production conditions across the two locations, the cottonseed yield was 1.87 Mg ha<sup>-1</sup>, 1.37 Mg ha<sup>-1</sup>, 1.86 Mg ha<sup>-1</sup>, and 1.59 Mg ha<sup>-1</sup>, respectively, for the E-stress, L-stress, R-stress, and the standard fertility. The seed cotton weight per boll, however, did not follow the same trend as the lint and cottonseed yields, with significant differences between nutrient treatments observed under Camilla 2020 SSDI condition only (Figure 2g,h). The seed cotton weight per boll under Camilla 2020 SSDI condition was least in the standard fertility (3.30 g kg<sup>-1</sup>) and greatest in R-stress (5.12 g kg<sup>-1</sup>).

### 3.2. Plant Height, Nodes, and Boll Development

Compared to R-stress, plant height was significantly reduced by L-stress under Camilla 2021 SSDI (25.0% reduction) and Midville 2021 rainfed (13.6% reduction) conditions (Figure 3a,b and Table S2). The effects of E-stress were minimal on plant height. The E-stress had a similar plant height as the R-stress and standard fertility. In addition, the number of main stem nodes was impacted by L-stress but not by E-stress (Figure 3c,d). A significant reduction in the number of main stem nodes occurred under the overhead irrigation conditions at both locations in 2021. The L-stress reduced the number of main stem nodes by 23.9% and 15.0%, respectively, under the overhead irrigation conditions in Camilla 2021 and Midville 2021. Compared to the E-stress and R-stress, the standard fertility had 21.3% and 17.7% lower number of main stem nodes, respectively, under Camilla 2021 overhead irrigation condition. The total (Figure 3e,f) and harvestable (Figure 3g,h) number of bolls were both significantly reduced by L-stress under Camilla 2021 SSDI conditions, but not under any production conditions in Midville. Compared to the R-stress, the reduction was very severe, 76.8% and 78.8% for the total and harvestable numbers of bolls, respectively. The E-stress, however, did not have a significant impact on the total and harvestable numbers of bolls, and also the R-stress had similar total and harvestable numbers of bolls as the standard fertility.

### 3.3. Biomass Accumulation

The effects of nutrient stress on biomass accumulation over time are shown in Table S3 and Figure 4. As already mentioned, biomass samples were collected at square initiation, 2-WoB, 7-WoB, and shortly before harvest, except for the Midville location where the samples were not collected at the 7-WoB stage. As expected, biomass accumulation significantly increased over the growth stages under all production conditions at the two locations. However, nutrient stress affected biomass accumulation at only the harvest stage. Significant differences were observed under all conditions in 2021 but not in 2020. Compared to R-stress, the E-stress did not affect biomass accumulation, whereas the L-stress and standard fertility significantly reduced biomass accumulation under four and one conditions, respectively. Averaged over all production conditions across the two locations, the E-stress, L-stress, R-stress, and standard fertility had total aboveground biomass of 11.7 Mg ha<sup>-1</sup>, 8.82 Mg ha<sup>-1</sup>, 12.2 Mg ha<sup>-1</sup>, and 10.4 Mg ha<sup>-1</sup>, respectively.

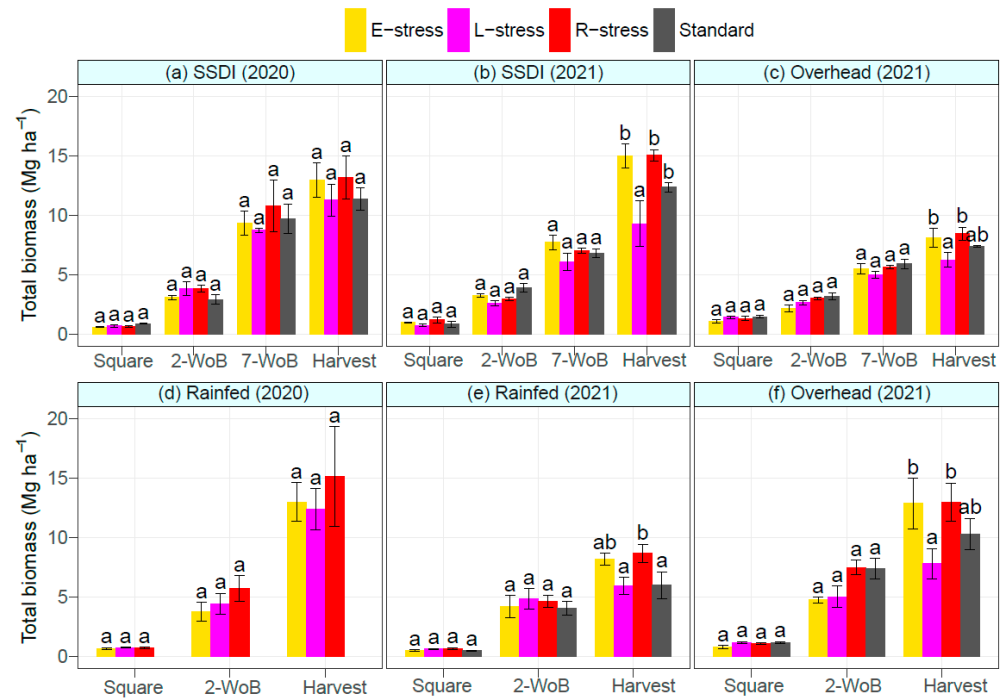


**Figure 3.** Nutrient stress effects on plant height (a,b), main stem nodes (c,d), and total (e,f) and harvestable (g,h) number of bolls in Camilla and Midville, GA under different production conditions. Within location and production conditions, means of nutrient stress treatments not sharing any letter are significantly different using the least squares means and adjusted Tukey multiple comparison procedure ( $p < 0.05$ ). Error bars indicate the standard error of the mean ( $n = 4$ ). SSDI: Sub-surface drip irrigation.

### 3.4. Fiber Quality

The effects of nutrient stress on fiber quality indicators across the different production conditions are shown in Table 3 and Table S4. Overall, the magnitude of the differences in fiber quality indicators among the nutrient treatments was minimal even though some of the test statistics were significant. Compared to the R-stress, the E-stress did not affect fiber length and strength, whereas the L-stress significantly reduced the fiber length and strength under Camilla 2021 SSDI condition only. The reduction was 4.23% and 2.02% for the fiber length and strength, respectively. Averaged over all production conditions across the two locations, the E-stress, L-stress, R-stress, and standard fertility had fiber lengths of 3.02 cm, 2.96 cm, 3.01 cm, and 2.97 cm, respectively, and a fiber strength of 31.1 g tex<sup>-1</sup>, 30.6 g tex<sup>-1</sup>, 30.9 g tex<sup>-1</sup>, and 30.7 g tex<sup>-1</sup>, respectively. The fiber uniformity was significantly increased in E-stress over the R-stress and standard fertility under Camilla 2021 overhead irrigation condition. It was also significantly increased in the E-stress over the R-stress and L-stress under the Midville 2021 rainfed condition. The E-stress, however, tended to decrease the micronaire, with an average reduction of 2.23% when compared to the R-stress. The

average micronaire across all production conditions at the two locations was 4.47, 4.57, 4.57, and 4.55 for the E-stress, L-stress, R-stress, and standard fertility, respectively. The RD was not significantly affected by nutrient stress under any production condition. In contrast to the RD, the +b was significantly reduced in the L-stress, and the effect was more obvious under Camilla 2020 SSDI and Midville 2021 rainfed conditions. The average +b under all conditions was 7.60%, 7.39%, 7.55%, and 7.53% for the E-stress, L-stress, R-stress, and standard fertility, respectively.



**Figure 4.** Nutrient stress effects on the total aboveground biomass in Camilla (a–c) and Midville (d–f), GA under different production conditions. Within production conditions and growth stage, means of nutrient stress treatments not sharing any letter are significantly different using the least squares means and adjusted Tukey multiple comparison procedure ( $p < 0.05$ ). Error bars indicate the standard error of the mean ( $n = 4$ ). SSDI: Sub-surface drip irrigation; WoB: Week of bloom.

**Table 3.** Nutrient stress effects on cotton fiber quality in Camilla and Midville under different production conditions.

| Nutrient Stress     | Fiber Length             | Fiber Strength           | Uniformity              | Micronaire                | RD                      | +b                       |
|---------------------|--------------------------|--------------------------|-------------------------|---------------------------|-------------------------|--------------------------|
|                     | cm                       | g tex <sup>-1</sup>      | %                       |                           | %                       |                          |
| Camilla (SSDI 2020) |                          |                          |                         |                           |                         |                          |
| E-stress            | 3.20 ± 0.01 <sup>a</sup> | 30.5 ± 0.3 <sup>a</sup>  | 81.9 ± 0.8 <sup>a</sup> | 4.08 ± 0.07 <sup>a</sup>  | 74.9 ± 0.2 <sup>a</sup> | 7.80 ± 0.07 <sup>a</sup> |
| L-stress            | 3.21 ± 0.01 <sup>a</sup> | 30.5 ± 0.3 <sup>a</sup>  | 81.1 ± 0.1 <sup>a</sup> | 4.32 ± 0.07 <sup>b</sup>  | 75.8 ± 0.2 <sup>a</sup> | 7.42 ± 0.15 <sup>b</sup> |
| R-stress            | 3.19 ± 0.03 <sup>a</sup> | 30.6 ± 0.1 <sup>a</sup>  | 81.5 ± 0.3 <sup>a</sup> | 4.22 ± 0.07 <sup>ab</sup> | 73.5 ± 0.4 <sup>a</sup> | 7.58 ± 0.09 <sup>b</sup> |
| Standard            | 3.17 ± 0.04 <sup>a</sup> | 30.1 ± 0.2 <sup>a</sup>  | 81.6 ± 0.8 <sup>a</sup> | 4.20 ± 0.09 <sup>ab</sup> | 74.3 ± 0.9 <sup>a</sup> | 7.47 ± 0.12 <sup>b</sup> |
| Camilla (SSDI 2021) |                          |                          |                         |                           |                         |                          |
| E-stress            | 3.10 ± 0.01 <sup>b</sup> | 30.5 ± 0.6 <sup>a</sup>  | 82.3 ± 0.3 <sup>a</sup> | 4.55 ± 0.03 <sup>a</sup>  | 74.0 ± 0.4 <sup>a</sup> | 6.92 ± 0.07 <sup>a</sup> |
| L-stress            | 2.95 ± 0.02 <sup>a</sup> | 29.7 ± 0.3 <sup>ab</sup> | 81.6 ± 0.4 <sup>a</sup> | 4.67 ± 0.03 <sup>a</sup>  | 75.9 ± 0.9 <sup>a</sup> | 6.83 ± 0.23 <sup>a</sup> |
| R-stress            | 3.08 ± 0.02 <sup>b</sup> | 30.3 ± 0.1 <sup>a</sup>  | 81.7 ± 0.2 <sup>a</sup> | 4.65 ± 0.03 <sup>a</sup>  | 74.2 ± 0.3 <sup>a</sup> | 6.85 ± 0.06 <sup>a</sup> |
| Standard            | 2.96 ± 0.02 <sup>a</sup> | 29.3 ± 0.3 <sup>b</sup>  | 81.6 ± 0.2 <sup>a</sup> | 4.60 ± 0.00 <sup>a</sup>  | 73.6 ± 0.2 <sup>a</sup> | 7.03 ± 0.15 <sup>a</sup> |

Table 3. Cont.

| Nutrient Stress          | Fiber Length              | Fiber Strength          | Uniformity               | Micronaire                | RD                      | +b                        |
|--------------------------|---------------------------|-------------------------|--------------------------|---------------------------|-------------------------|---------------------------|
|                          | cm                        | g tex <sup>-1</sup>     | %                        |                           | %                       |                           |
| Camilla (Overhead 2021)  |                           |                         |                          |                           |                         |                           |
| E-stress                 | 3.04 ± 0.01 <sup>c</sup>  | 27.8 ± 0.2 <sup>a</sup> | 82.1 ± 0.2 <sup>a</sup>  | 4.60 ± 0.04 <sup>ab</sup> | 74.7 ± 0.7 <sup>a</sup> | 6.92 ± 0.14 <sup>a</sup>  |
| L-stress                 | 2.93 ± 0.02 <sup>ab</sup> | 27.0 ± 0.4 <sup>a</sup> | 81.7 ± 0.2 <sup>ab</sup> | 4.58 ± 0.05 <sup>ab</sup> | 74.3 ± 0.6 <sup>a</sup> | 6.78 ± 0.05 <sup>a</sup>  |
| R-stress                 | 2.99 ± 0.02 <sup>bc</sup> | 27.8 ± 0.3 <sup>a</sup> | 81.4 ± 0.2 <sup>b</sup>  | 4.68 ± 0.03 <sup>b</sup>  | 73.6 ± 0.9 <sup>a</sup> | 6.97 ± 0.12 <sup>a</sup>  |
| Standard                 | 2.90 ± 0.03 <sup>a</sup>  | 27.3 ± 0.3 <sup>a</sup> | 81.3 ± 0.4 <sup>b</sup>  | 4.47 ± 0.06 <sup>a</sup>  | 74.7 ± 0.6 <sup>a</sup> | 6.95 ± 0.06 <sup>a</sup>  |
| Midville (Rainfed 2020)  |                           |                         |                          |                           |                         |                           |
| E-stress                 | 2.90 ± 0.03 <sup>a</sup>  | 32.2 ± 0.4 <sup>a</sup> | 83.3 ± 0.3 <sup>a</sup>  | 4.55 ± 0.12 <sup>a</sup>  | 77.8 ± 0.2 <sup>a</sup> | 7.88 ± 0.22 <sup>a</sup>  |
| L-stress                 | 2.93 ± 0.04 <sup>a</sup>  | 32.5 ± 0.4 <sup>a</sup> | 83.2 ± 0.4 <sup>a</sup>  | 4.65 ± 0.03 <sup>a</sup>  | 77.5 ± 0.1 <sup>a</sup> | 7.85 ± 0.13 <sup>a</sup>  |
| R-stress                 | 2.98 ± 0.02 <sup>a</sup>  | 33.0 ± 0.8 <sup>a</sup> | 83.5 ± 0.3 <sup>a</sup>  | 4.47 ± 0.07 <sup>a</sup>  | 77.7 ± 0.2 <sup>a</sup> | 8.18 ± 0.12 <sup>a</sup>  |
| Standard                 | na                        | na                      | na                       | na                        | na                      | na                        |
| Midville (Rainfed 2021)  |                           |                         |                          |                           |                         |                           |
| E-stress                 | 2.94 ± 0.03 <sup>b</sup>  | 32.6 ± 0.6 <sup>a</sup> | 83.3 ± 0.2 <sup>a</sup>  | 4.62 ± 0.13 <sup>a</sup>  | 76.7 ± 0.3 <sup>a</sup> | 8.10 ± 0.09 <sup>b</sup>  |
| L-stress                 | 2.81 ± 0.04 <sup>a</sup>  | 30.9 ± 0.5 <sup>a</sup> | 82.4 ± 0.2 <sup>b</sup>  | 4.70 ± 0.00 <sup>a</sup>  | 76.0 ± 0.2 <sup>a</sup> | 7.55 ± 0.06 <sup>a</sup>  |
| R-stress                 | 2.89 ± 0.02 <sup>ab</sup> | 31.9 ± 0.2 <sup>a</sup> | 82.5 ± 0.3 <sup>b</sup>  | 4.70 ± 0.07 <sup>a</sup>  | 75.7 ± 0.1 <sup>a</sup> | 7.90 ± 0.08 <sup>ab</sup> |
| Standard                 | 2.88 ± 0.03 <sup>ab</sup> | 31.9 ± 0.5 <sup>a</sup> | 83.0 ± 0.4 <sup>ab</sup> | 4.72 ± 0.05 <sup>a</sup>  | 76.2 ± 0.2 <sup>a</sup> | 7.75 ± 0.18 <sup>ab</sup> |
| Midville (Overhead 2021) |                           |                         |                          |                           |                         |                           |
| E-stress                 | 2.94 ± 0.03 <sup>a</sup>  | 32.8 ± 0.2 <sup>a</sup> | 83.0 ± 0.4 <sup>a</sup>  | 4.42 ± 0.09 <sup>a</sup>  | 77.4 ± 0.2 <sup>a</sup> | 7.97 ± 0.23 <sup>a</sup>  |
| L-stress                 | 2.95 ± 0.03 <sup>a</sup>  | 33.2 ± 0.8 <sup>a</sup> | 83.4 ± 0.2 <sup>a</sup>  | 4.53 ± 0.09 <sup>ab</sup> | 77.8 ± 0.0 <sup>a</sup> | 7.92 ± 0.25 <sup>a</sup>  |
| R-stress                 | 2.91 ± 0.02 <sup>a</sup>  | 32.0 ± 0.1 <sup>a</sup> | 83.2 ± 0.3 <sup>a</sup>  | 4.70 ± 0.04 <sup>ab</sup> | 78.1 ± 0.2 <sup>a</sup> | 7.85 ± 0.09 <sup>a</sup>  |
| Standard                 | 2.92 ± 0.03 <sup>a</sup>  | 32.3 ± 0.4 <sup>a</sup> | 83.5 ± 0.5 <sup>a</sup>  | 4.80 ± 0.17 <sup>b</sup>  | 77.6 ± 0.2 <sup>a</sup> | 7.82 ± 0.03 <sup>a</sup>  |

Within location and production conditions, means of nutrient stress treatments not sharing any letter are significantly different using the least squares means and adjusted Tukey multiple comparison procedure ( $p < 0.05$ ). Values represent the mean ± standard error. SSDI: Sub-surface drip irrigation; na: Not available; RD, fiber reflectance; +b, fiber yellowness.

#### 4. Discussion

The residual soil nutrients, which were within the typical range [21], may have met the nutritional needs of the crop by the square stage, as depicted by the lack of significant impact of E-stress on the total aboveground biomass accumulated at the square stage at all production conditions. As an indeterminate crop, cotton can exhibit a high degree of plasticity in growth [11,28,29], which may infer some level of tolerance to partial nutrient stress. Nonetheless, optimum nutrient management is critical for achieving high yield and efficiency in cotton [11]. Nutritional demand for cotton in the early season is reported to be low [7,11,12]. Bassett et al. [12] observed that at the first flower stage, the N, P, K, Ca, and Mg accumulated in the aboveground components of cotton were <15% of the total. In addition, 2–4% of the total seasonal aboveground biomass had accumulated at the square stage [12]. The average aboveground biomass accumulated by the square stage in this study was 8.2% of that accumulated by harvest.

In addition to residual soil nutrients, mineralization of crop residues and organic matter is another good source of nutrients for crops [30–32]. Organic matter at the experimental sites was low to have contributed to any appreciable levels of nutrients (2.90 g kg<sup>-1</sup> in Camilla and 4.67 g kg<sup>-1</sup> in Midville). However, residues of the previous crops (corn and peanut) and the use of rye cover crops may have affected the overall nutrient supply. As a biological process, the mineralization of crop residues depends on several abiotic and biotic factors, including temperature, rainfall, soil properties, the chemical composition of the crop residues, and the structure and composition of microbial communities [33–36]. Mineralization of the peanut residues would occur at a greater rate than those of the corn residues or the rye cover crop, as a result of the lower C:N ratio of the peanut residues. Synchronizing fertilizer application and nutrient release from crop residues with plant nutrient demand could enhance crop productivity while reducing over application of mineral fertilizers [33,34].

The E-stress also had no impact on cotton yield, which is consistent with observations made from previous studies that investigated the one-time application of nutrients in cotton [37,38]. In general, the application of N, P, and K at only the first flower stage was reported to maximize nutrient utilization while minimizing the impact on the environment [37,38]. The standard fertility received lower rates of nutrients than the E-stress and R-stress. Compared to the E-stress and R-stress, the standard fertility underperformed, with statistical significance in lint and cottonseed yields observed in Camilla 2021 under both the SSDI and overhead irrigation conditions. While modern cotton cultivars have better nutrient use efficiencies [6,7], the observations of this study indicate they also respond to high nutrient levels. According to Pabuayon et al. [7], genetic improvements to enhance the nutrient efficiency of modern cultivars may have changed their organ nutrient accumulation and requirement rates.

The L-stress received just 30–40% of the nutrient rate of the R-stress, which was applied one time at the early stage of planting. The results showed the L-stress had significantly lower lint and cottonseed yields than the R-stress under four out of the six production conditions tested in this study. Compared to the standard fertility, the L-stress had significantly lower lint and cottonseed yields under just one (Camilla 2021 SSDI condition) out of the five production conditions. As already mentioned, the standard fertility was not tested under the Midville 2020 rainfed condition. Nutrient uptake in cotton peaks from flowering through fruiting, and then slows as the bolls mature [11]. This explains why biomass accumulation was not adversely impacted by L-stress at the square stage, but yield and biomass accumulation were significantly reduced by L-stress at maturity. The 30–40% nutrient rates applied to the L-stress plots may have been depleted by the later growth stages.

Effects of nutrient stress on cotton fiber quality were not consistent across the different production conditions. Where significant, the E-stress tended to increase the fiber length, fiber strength, and uniformity, which was desirable. However, it decreased the micronaire and increased the +b, reflecting poor quality. In contrast, the L-stress tended to decrease the +b. Reported effects of nutrient application on cotton fiber quality are often inconsistent and vary across locations and cultivars [39–41]. Findings from a study, which evaluated seven cotton cultivars under 33 environments in Georgia, showed that production conditions that enhanced yield also led to improved fiber quality [42]. The E-stress and R-stress had the greatest lint yield but had undesirable micronaire and +b properties, which could be due to the high N rates applied. Sui et al. [39] observed a negative correlation between +b and leaf N content. Overall, however, the magnitude of the differences in the fiber quality indicators observed in this study was small and did not affect the grading class.

The global textile market is competitive and fiber quality is critical to ensuring good prices. Moreover, fiber quality affects manufacturing processes and the ultimate use of cotton fiber. Of the fiber quality indicators, color has the highest contribution to the price of cotton [41,43]. Chakraborty et al. [43] reported that color, cleanliness, micronaire, length, and strength contributed 30%, 23%, 22%, 20%, and 5%, respectively, to the price premium paid toward cotton fiber quality. According to McVeigh [44], a drop from Middling (31) to Strict Low Middling (41) can cause Australian farmers to lose about \$760 ha<sup>-1</sup>. In the USA, the annual cotton price statistics report for the 2021–2022 season by the USDA-AMS showed quotations for color 41, leaf 4, staple 34, micronaire 35–36 and 43–49, strength of 27.0–28.9 g tex<sup>-1</sup>, and uniformity of 81% to be ~\$2.52 kg<sup>-1</sup> [45]. The quotation for a better cotton fiber quality (color 31, leaf 3, staple 34, micronaire 35–36 and 43–49, strength of 27.0–28.9 g tex<sup>-1</sup>, and uniformity of 81%) increased by ~2.29 cents kg<sup>-1</sup> [45].

## 5. Conclusions

Cotton yield was not adversely impacted by E-stress. However, the L-stress significantly reduced the lint and cottonseed yields under four and one production conditions, when compared to the R-stress and standard fertility, respectively. The E-stress and R-stress had better lint and cottonseed yield than the standard fertility, indicating modern cultivars

can respond to high nutrient levels. Significant nutrient stress effects on fiber quality were observed but the magnitude of the differences was small and it did not affect the grading class. The minimal impact of E-stress on cotton yield and quality in this study suggests that the rates of nutrients often applied in the early season can be reduced. More tailored nutrient application rates, based on soil and plant tissue analyses, could then be applied shortly before the reproductive phase of the crop. Such a system will help optimize crop nutrition by synchronizing nutrient availability with crop demand.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agronomy13010064/s1>, Table S1: Fertilizers applied as the main sources of the different nutrient elements in Camilla and Midville; Table S2: *P*-values of the main effects and interaction effects of nutrient stress and production conditions on the growth and productivity of cotton in Camilla and Midville; Table S3: *P*-values of the main effects and interaction effects of nutrient stress and growth stage on biomass accumulation of cotton in Camilla and Midville under different production conditions; Table S4: *P*-values of the main effects and interaction effects of nutrient stress and production conditions on the fiber quality of cotton in Camilla and Midville.

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## Abbreviations

E-stress, early-season nutrient stress; L-stress, late-season nutrient stress; R-stress, reduced nutrient stress; SSDI, sub-surface drip irrigation; WoB, week of bloom; RD, fiber reflectance; +b, fiber yellowness

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