SENSOR-BASED PLANT GROWTH REGULATOR MANAGEMENT IN COTTON: PLOT-LEVEL AND WITHIN-PLANT YIELD DISTRIBUTION

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Abstract

Cotton yield is distributed across canopy thirds, and the use of plant growth regulators (PGRs) can modify the balance between vegetative and reproductive growth, affecting fruiting and yield. Drone-mounted sensors can support plant growth monitoring and the generation of maps for variable-rate PGR application. This study compared traditional PGR management, with fixed timing and rate, with sensor-based management strategies, evaluating application rate, timing, yield, fiber quality, and within-plant yield distribution. The experiment was conducted at the University of Georgia, in Watkinsville, under two environments: dryland and irrigated. Three PGR management treatments were tested: i) Fixed – PGR applied at fixed timing and rates following the farm schedule, with 146 mL ha^{-1} initially and 292 mL ha^{-1} at cutout; ii) VR_1 – weekly sensor-based PGR applications, with rates varying according to sensor-estimated growth and applied as needed, up to once per week; and iii) VR_2 – biweekly sensor-based PGR applications, with rates varying according to sensor data and applied as needed, up to once every two weeks. Manual measurements of plant height and node number were performed, along with weekly drone flights equipped with LiDAR and a multispectral sensor. Continuous maps of plant height and node number were used in the MEPRT model to generate PGR recommendations. Eight days before harvest, 10 plants per plot were collected to evaluate yield distribution by plant third and boll position. Plot-level yield was determined by harvesting the two center rows with a plot cotton picker. Total PGR applied was 438 mL ha^{-1} for Fixed, 438–474 mL ha^{-1} for VR_1, and 438–514 mL ha^{-1} for VR_2. High agreement was observed between manually measured plant height and LiDAR-estimated height, as well as between observed node number and model-predicted node number. At the plot level, fiber yield differed among treatments only under dryland conditions, with the highest value observed in VR_2 and the lowest in VR_1, possibly due to the timing of applications in relation to water availability. In the plant mapping assessment, VR_1 showed a trend toward greater bolls m^{-2}, while Fixed had greater mean boll weight. In addition, there was an interaction between plant third and boll position, indicating that proximal positions in the middle and lower thirds contributed more to yield, whereas distal positions and the upper third had lower contributions. These results indicate that sensor-based PGR recommendations can support variable-rate management, reduce dependence on manual assessments, and maintain or increase cotton yield.

Keywords: Variable-rate application, LiDAR, precision agriculture, remote sensing, cotton mapping.

Introduction

Cotton is an indeterminate growth plant, with high plasticity and strong responses to environmental conditions and management practices, especially regarding plant arrangement, nutrition, water availability, and the use of plant growth regulators (Oosterhuis et al. 2020). Due to this growth pattern, the crop may develop excessive vegetative growth, canopy shading, and abscission of reproductive structures, compromising yield and making mechanical harvest more difficult (Rossi et al., 2020; Raphael et al., 2019).

In this context, plant growth regulators, especially mepiquat chloride and chlormequat chloride, are widely used in cotton management to control excessive vegetative growth and promote a more balanced plant architecture (Murtza et al., 2022). These regulators act mainly by reducing internode elongation, resulting in shorter plants, less disorganized vegetative growth, and better distribution of reproductive structures throughout the canopy. By limiting plant height, the plant tends to have less internal competition for photoassimilates between vegetative and reproductive structures. Thus, part of the reserves that would be directed to excessive stem, branch, and leaf growth may be redistributed to productive structures, such as squares, flowers, and bolls. This effect contributes to a better balance between vegetative and reproductive growth, favoring the retention of fruiting structures and boll formation. In addition, controlling plant height and excessive branching improves canopy architecture, allowing greater light penetration into the lower and middle layers of the plant. This improved light distribution may favor photosynthetic activity in different canopy positions and contribute to greater uniformity in boll formation and maturation. Plants with a more compact and uniform architecture also facilitate mechanical harvest, reduce field losses, and improve operational efficiency (Rossi et al., 2020; Balkcom et al., 2022).

However, cotton response to plant growth regulators depends directly on the applied rate, application timing, and crop development conditions. Therefore, these products should be understood as tools for fine-tuning plant growth, rather than inputs with uniform effects across all production environments. The definition of rate and application timing should consider plant vigor, weather conditions, cropping system, cultivar, and the productive potential of the field. Excessive applications or applications performed at inappropriate times may overly restrict vegetative growth, limit the formation of reproductive structures, and compromise yield. Thus, proper PGR management aims to control excessive vegetative growth without impairing reproductive development, preserving or improving cotton yield (Priyadarshini et al., 2023; Balkcom et al., 2022; Snider and Kawakami, 2014).

In this context, remote sensing emerges as an important tool to support more precise monitoring of cotton growth under real field conditions. Using drone-mounted sensors, it is possible to estimate traits related to plant vigor and structure, such as canopy height, allowing the identification of spatial variability within the field. In addition, predictive models can be used to estimate plant node number from remote sensing information, expanding the ability to characterize actual crop development in the field. These data can support decision-making for plant growth regulator management, enabling applications that are better adjusted to the actual needs of the plants and the specific conditions of each area of the field (Yuan et al., 2018; Landivar et al., 1995).

The objectives of this study were to: I) determine the ability of drone-mounted sensors to estimate plant height and node number in cotton; II) compare conventional plant growth regulator management, based on fixed application timing and rates, with sensor-based management strategies; III) evaluate the effects of these management strategies on the total PGR rate applied, lint yield, and fiber quality under irrigated and dryland production systems; and IV) assess how these management strategies can modify fruit distribution within the plant.

Materials and methods

The study was conducted under two production environments, irrigated and dryland, at the J. Phil Campbell Research and Education Center, University of Georgia, located near Watkinsville, Georgia. Cotton was planted on May 25, 2025, at an approximate seeding rate of 8.2 seeds m^{-1}. Each experimental plot measured 7.32 m in width by 9.14 m in length and consisted of eight rows spaced 0.91 m apart. The experiment was arranged in a randomized complete block design with four replications in two environments: irrigated and dryland.

Treatments consisted of three plant growth regulator management strategies: i) fixed timing and rate management (Fixed), in which applications followed the farm schedule, with an initial rate of 146 mL ha^{-1} and a final rate of 242 mL ha^{-1} at cutout; ii) sensor-based management with the possibility of weekly applications (VR_1), in which rates were adjusted according to estimated plant growth and applied as needed, with a maximum frequency of once per week; and iii) sensor-based management with the possibility of biweekly applications (VR_2), in which rates were also determined based on sensor data and applied as needed, with a maximum frequency of one application every two weeks. The product MEP6X (23.5%) was used in all applications.

Throughout the experiment, plant height and node number were monitored weekly through manual assessments, complemented by drone flights equipped with LiDAR and multispectral sensors. These aerial operations were performed near solar noon, between 10:00 a.m. and 2:00 p.m., to ensure optimal illumination conditions, reduce shading, and improve light uniformity. The collected data were used to generate continuous field maps, with plant height derived directly from LiDAR and node number estimated from the combination of spectral, elevation, and meteorological data using machine learning models. Subsequently, plot-level means were calculated for these variables, and these values were used as inputs for the MEPRT model, as described by Landivar et al. (1995), which generated plant growth regulator recommendations. The recommended rates were then applied with a backpack sprayer at the respective recommended timings.

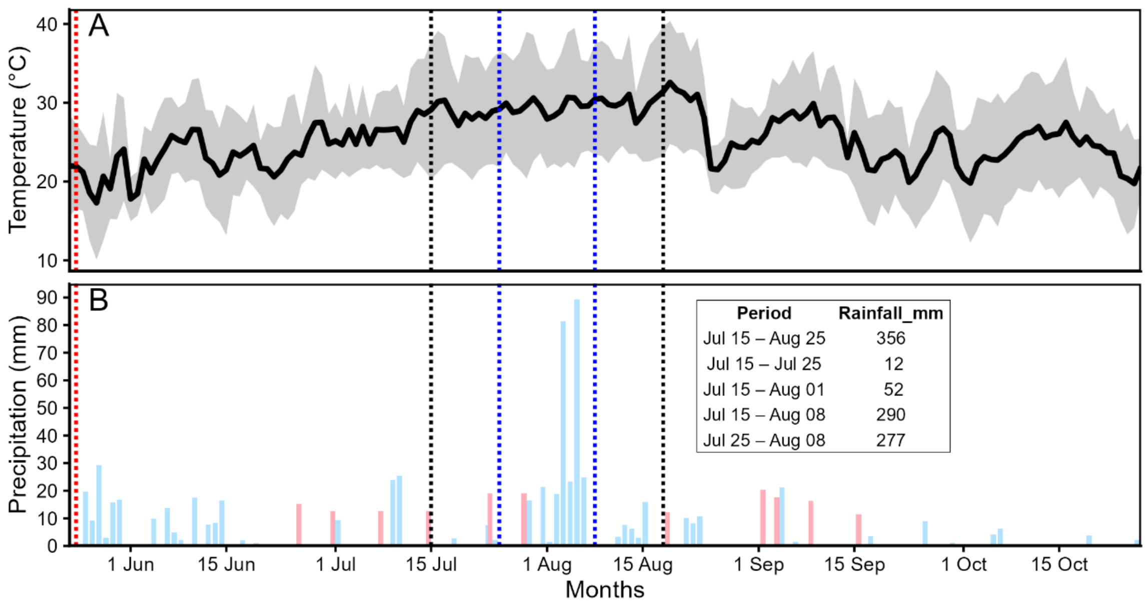

Fig. 1 Maximum, minimum, and average temperature in Celsius (a), and precipitation and irrigation values (b) according to the months. The blue bars represent precipitation, and the pink bars represent irrigation. The red dashed line indicates the planting date, the blue dashed lines indicate the beginning and end of the plant growth regulator application period, and the black dashed lines indicate 10 days before the first application and 10 days after the last application

Between July 25 and August 8, the period corresponding to plant growth regulator management, cumulative precipitation was 277 mm. To characterize the water conditions preceding the applications, rainfall during the 10 days before the first intervention, starting on July 15, was also considered. In this context, accumulated rainfall was only 12 mm between July 15 and July 25, reached 52 mm between July 15 and August 1, and totaled 290 mm between July 15 and August 8, indicating a substantial increase in water availability throughout the period and, especially, greater water supply conditions at the time of the third application. In parallel, in addition to the irregular rainfall distribution, several days with maximum temperatures above the range considered ideal for the crop (>31.8 °C) were observed, with values ranging from 35.0 to 40.4 °C (Fig. 1), while minimum temperatures remained, for most of the period between July and mid-August, above 20 °C. Four potential application timings were carried out at 61, 68, 75, and 81 days after planting. All treatments received two applications during this period, differing only in the timing and rate of the first application, according to the treatment or the recommendation generated. The last application coincided with cutout and consisted of a fixed rate of 292 mL ha^{-1} in all plots. At the end of the cycle, the Fixed treatment accumulated 438 mL ha^{-1}, whereas VR_1 totaled 438 to 475 mL ha⁻¹ and VR_2 ranged from 438 to 514 mL ha⁻¹.

Yield was estimated by harvesting two rows from each plot using a plot harvester, with seed cotton weight recorded individually for each experimental unit. Then, one sample from each plot was separated for processing in a bench-top gin to determine ginning outturn and lint yield. Subsequently, a subsample of the obtained lint was submitted for fiber technological property analysis using HVI equipment (High Volume Instrument). The data were analyzed in R using a linear mixed model, considering plant growth regulator management as a fixed effect and blocks as a random effect. Treatment significance was assessed by type III ANOVA, and means were compared using estimated marginal means with the emmeans package.

At the plant level, fruit distribution mapping was performed on 10 plants per plot. Plants were manually collected eight days before harvest and evaluated individually. In each plant, fruits were identified according to fruiting branch and branch position, considering positions 1, 2, and 3+. Fruiting branches were grouped into the lower, middle, and upper thirds of the plant. For each combination of plant third and fruit position, fruit number and boll weight were determined, allowing the spatial distribution of production within the plant to be characterized. Statistical analysis was performed separately for each environment, irrigated and dryland. A linear model was fitted considering the effects of block, plant growth regulator management, plant third, boll position, and their interactions. Analysis of variance was conducted using type III sums of squares, and the significance of effects was evaluated by the F test. When significant interactions occurred, effects were further examined using estimated marginal means with the emmeans package, and means were compared at the 5% probability level.

Results and discussion

Plot level

There was a strong correspondence between plant heights measured in the field and those estimated from LiDAR data, with a coefficient of determination of 0.97, demonstrating the high precision of this approach for quantifying cotton plant height (Fig. 2). For this estimation, it is necessary to previously define the soil surface, which is used as the reference plane for calculating canopy height. From this reference, plant height is obtained as the difference between terrain elevation and the returns located in the upper portion of the vegetation cover (Jimenez-Berni et al., 2018). Thus, the accuracy of the estimate depends on the correct distinction between points associated with the soil and those related to the top of the canopy.

Overall, the values generated by LiDAR showed high agreement with manual measurements, demonstrating the consistency of the method. However, in the assessment performed on August 12, 2025, at a more advanced stage of crop development, points I-202 and I-401 deviated from the predominant linear trend. This behavior suggests that, under greater canopy closure, the reduction in ground-level returns may hinder the precise definition of the reference surface, increasing the uncertainty associated with plant height estimation.

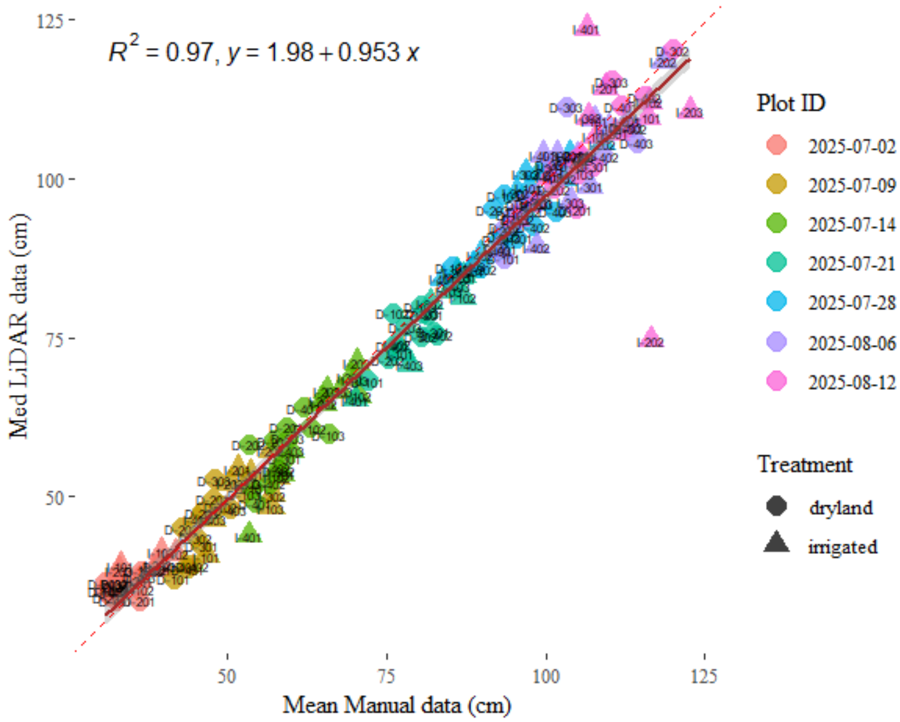

Fig. 2 Comparison between plant height measurements obtained manually and by LiDAR on different dates, represented by colors. Symbols indicate the growing environments: dryland (○) and irrigated (Δ)

Node number showed strong agreement between field-measured values and those predicted by the model, with a coefficient of determination of 0.97 and a root mean square error of 0.66, indicating high predictive capacity for this variable (Fig. 3). This performance indicates that the integration of multispectral, elevation, and meteorological information into machine learning models allowed cotton node number to be accurately estimated and continuous maps of its spatial distribution in the field to be generated. Thus, the predictive model demonstrated potential to represent actual plant development and support decision-making related to plant growth regulator management.

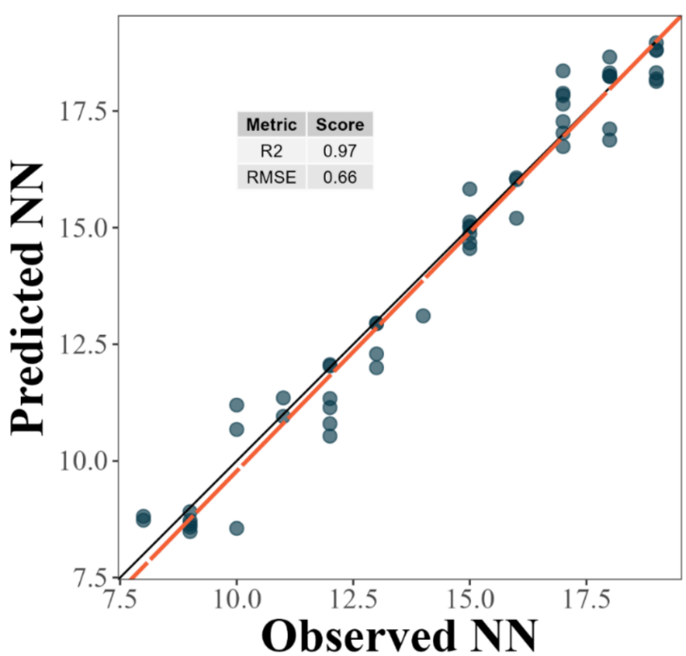

Fig. 3 Relationship between the observed plant node number (manual measurements) and the node number predicted from sensor data

According to Table 1, lint yield differed among treatments only under dryland conditions, with the highest value observed in VR_2, which showed 4.4% greater yield than VR_1. The Fixed treatment showed an intermediate response and did not differ from either VR_1 or VR_2. For fiber yellowness index (+b), differences occurred only in the irrigated environment, where VR_1 showed a value 7% higher than VR_2. The other yield components, such as boll number, boll weight, and ginning outturn, as well as the other fiber quality parameters, did not differ among treatments in either environment and remained within the required commercial standards.

These results indicate that the different plant growth regulator management strategies had limited effects on yield components and on most fiber technological attributes. However, the response observed for lint yield under dryland conditions and for the +b index in the irrigated environment suggests that application timing and rate may influence specific aspects of crop performance. Proper definition of these applications is essential in cotton management, as it can affect the balance between vegetative and reproductive growth, with possible effects on yield and traits related to the visual quality of lint, such as fiber yellowness (Murtza et al., 2022).

Table 1. Fiber quality and yield components of cotton as affected by plant growth regulator management treatments (Fixed, VR_1, and VR_2) under dryland and irrigated conditions. Means followed by the same letter within each environment do not differ at the 5% probability level.

		Dryland				Irrigated			
		Fixed	**VR_1**	**VR_2**	**Value p**	**Fixed**	**VR_1**	**VR_2**	**Value p**
Lint yield	*kg ha^{-1}*	2618 ab	2564 b	2677 a	0.02^{*}	2644 a	2547 a	2468 a	0.41^{ns}
Bolls	*no. m^{-2}*	111 a	120 a	114 a	0.59^{ns}	119 a	101 a	103 a	0.34^{ns}
Boll weight	*g*	5.25 a	4.86 a	5.32 a	0.52^{ns}	4.69 a	5.81 a	5.47 a	0.31^{ns}
Ginning outturn	*%*	44.79 a	44.20 a	44.97 a	0.34^{ns}	44.41 a	44.74 a	45.02 a	0.53^{ns}
Plant density	*n/m^{2}*	6.3 a	6.7 a	6.4 a	0.60^{ns}	6.2 a	6 a	5.9 a	0.57^{ns}
Color Grad	*	49 a	49 a	49 a	1.00^{ns}	49 a	49 a	51 a	0.36^{ns}
Leaf Grad	*	8 a	8 a	8 a	1.00^{ns}	8 a	7 a	8 a	0.11^{ns}
MIC	*µg inch^{-1}*	4.20 a	4.52 a	4.4 a	0.07^{ns}	4.17 a	4.40 a	4.35 a	0.24^{ns}
LEN	*mm*	37.5 a	38.0 a	37.5 a	0.22^{ns}	37.25 a	37.5 a	37.25 a	0.74^{ns}
STR	*g/tex*	30.65 a	30.00 a	29.92 a	0.07^{ns}	30.40 a	30.17 a	30.87 a	0.39^{ns}
UI	*%*	83.67 a	83.62 a	84.15 a	0.38^{ns}	83.65 a	83.95 a	83.60 a	0.68^{ns}
Rd	*%*	71.30 a	71.65 a	71.45 a	0.93^{ns}	70.95 a	72.35 a	71.00 a	0.12^{ns}
+b	*	6.87 a	6.80 a	7.32 a	0.40^{ns}	7.25 ab	7.35 a	6.87 b	0.01^{*}

ns: not significant; * p ≤ 0.05. Color grade: commercial classification; leaf grade: visual scale; MIC: micronaire; LEN: fiber length; STR: fiber strength; UI: length uniformity; Rd: reflectance; +b: yellowness index.

Lint yield in the VR_2 treatment was 4.41% higher than in VR_1 under dryland conditions (Fig. 4). This result may be associated with the temporal distribution of rainfall and the timing of plant growth regulator applications. Between June 15 and July 8, no rainfall events were recorded at the experimental site. Subsequently, on July 9 and 10, rainfall events of 23 and 25 mm occurred, respectively; however, after this period, there were again approximately 12 days without considerable rainfall. In this context, most applications in the VR_1 and Fixed treatments occurred during the dry spell, whereas part of the VR_2 applications was performed after the rainfall events.

Although the application of plant growth regulators in cotton may contribute to increased yield by modulating plant architecture and improving the balance between vegetative and reproductive growth, its efficiency depends directly on the environmental conditions at the time of application (Tung et al., 2023). Under water and heat stress conditions, plant vegetative growth already tends to be naturally limited. Thus, applying a growth regulator during this period may intensify growth restriction, excessively reducing vegetative development and possibly compromising the plant’s ability to sustain reproductive structures. Therefore, the better performance observed in VR_2 may be related to the fact that part of the applications occurred after and during rainfall events, at a time of greater water availability and, possibly, greater plant responsiveness to plant growth regulator management.

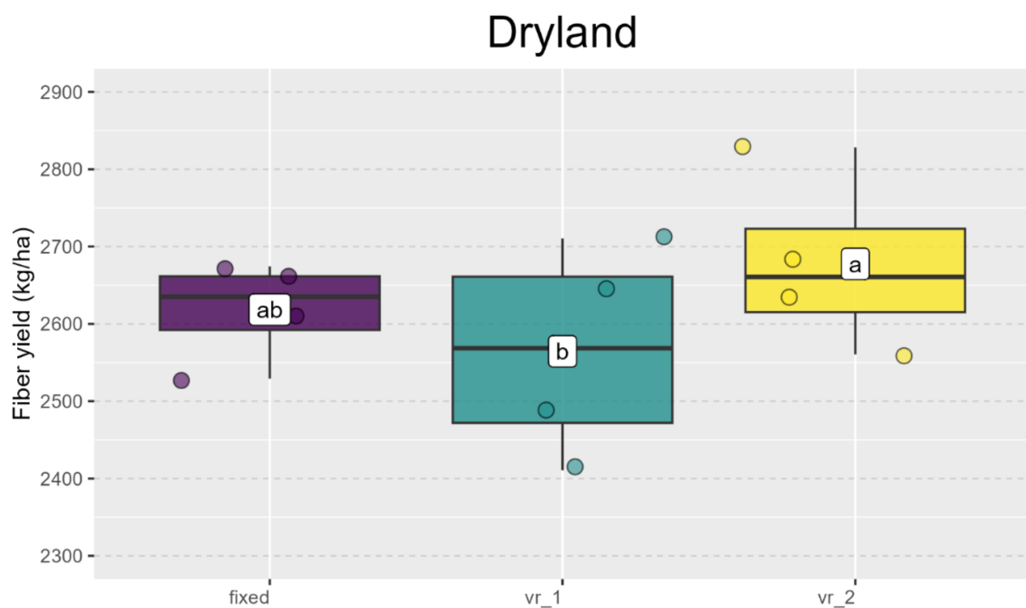

Fig. 4 Cotton fiber yield as a function of treatments (Fixed, VR_1 and VR_2) under irrigated and dryland conditions. Means followed by the same letter do not differ significantly ($p \leq 0.05$)

The yellowness index (+b) and reflectance degree (Rd) are among the main parameters used to evaluate color and classify cotton fiber, and they may influence commercial value, spinning performance, and the appearance of yarn and fabric. The +b index represents the intensity of yellowish or creamy pigmentation in the fiber, with higher values indicating greater lint yellowness, a generally less desirable trait. In contrast, Rd expresses reflectance, that is, the whiteness or brightness of the lint, with higher values associated with brighter and visually more desirable fibers. These parameters may be influenced by several factors, such as genotype, crop management, prolonged exposure to weather conditions, delayed harvest, moisture at harvest, temperature, presence of impurities, and storage conditions (Scarpin et al., 2023; Ibrahim et al., 2018; Pedroza et al., 2006). In general, higher Rd values and lower +b values are associated with whiter fibers, better visual classification, and greater commercial value. In the present study, the observed reflectance and yellowness values remained within suitable ranges for lint commercialization (Zardari et al., 2025).

Plant growth regulator applications performed at different timings may have influenced plant development and boll opening, resulting in differences in the duration of fiber exposure to environmental conditions. In this sense, it is possible that some treatments, such as VR_1, had open bolls for a longer period before harvest, increasing lint exposure to moisture, radiation, and temperature variations. This longer exposure period may have contributed to the increase in fiber yellowness compared with the VR_2 treatment under irrigated conditions.

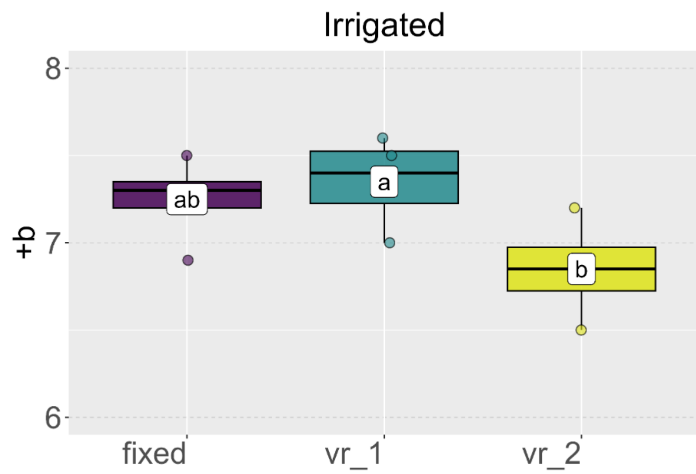

Fig. 5 Fiber yellowness index (+b) as a function of the Fixed, VR_1, and VR_2 treatments under irrigated conditions. Means followed by the same letter do not differ at the 5% probability level

Plant level

The mapping assessments revealed a significant interaction between canopy third and fruiting position in both environments for all production variables analyzed. This result demonstrates that the distribution of these variables within the plant depends on the combination of vertical position in the canopy and fruit position on the branch. In contrast, the treatment effect was less extensive, with differences observed only for the number of bolls per square meter under dryland conditions and for boll weight in both environments (Table 2).

In cotton, leaves and reproductive organs located in the upper third of the canopy generally receive greater radiation availability, which may favor higher photosynthetic activity. However, because these organs are formed later, they have a shorter period for boll initiation, development, and maturation, causing fruiting in this stratum to be concentrated predominantly in the primary and secondary positions. In contrast, the lower third of the plant tends to be more susceptible to shading and senescence, especially when plant growth regulator management does not provide adequate canopy architecture (Xing et al., 2018; Wang et al., 2021). This dynamic, however, is also influenced by nitrogen availability and the genetic characteristics of the cultivar, factors that may alter the initiation and retention of reproductive structures in more distal positions (Wu et al., 2023). Therefore, management practices that favor light interception and distribution within the canopy may increase crop productive efficiency, reinforcing that cotton yield expression results from a close relationship between plant third and the occupation of different fruiting positions.

Table 2. P-values for fiber yield, bolls m^{-2}, and boll weight considering the effects of treatment, plant third, boll position, and their interactions under irrigated and dryland conditions.

	Irrigated			**Dryland**		
	Fiber yield	Bolls m^{-2}	Boll weight	Fiber yield	Bolls m^{-2}	Boll weight
Treatment	0.878^{ns}	0.130^{ns}	0.026^{*}	0.844^{ns}	0.060†	0.000^{***}
Third	0.000^{***}	0.000^{***}	0.000^{***}	0.000^{***}	0.000^{***}	0.000^{***}
Position	0.000^{***}	0.000^{***}	0.000^{***}	0.000^{***}	0.000^{***}	0.003^{*}
Treatment x Third	0.598^{ns}	0.723^{ns}	0.314^{ns}	0.953^{ns}	0.805^{ns}	0.943^{ns}
Treatment x Position	0.875^{ns}	0.908^{ns}	0.380^{ns}	0.972^{ns}	0.442^{ns}	0.966^{ns}

Third x Position	0.000***	0.000***	0.000***	0.000^{***}	0.000^{***}	0.041^{*}
Treatment x Third x Position	0.336^{ns}	0.977ns	0.251^{ns}	0.942^{ns}	0.922^{ns}	0.835^{ns}

ns: not significant; † p < 0.10; * p < 0.05; *** p < 0.001. Values of 0.000 were reported as p < 0.001.

The number of bolls obtained from plant mapping differs from that determined at the plot level. While plot-level assessment directly represents productive performance per unit area, integrating stand variability and the total contribution of plants, mapping represents an estimate obtained from sampled plants, with emphasis on boll distribution among plant thirds and reproductive positions. Thus, even after area standardization, mapping data reflect the structural organization of production within the plant, whereas plot-level data express the final productive outcome of the system. For this reason, the values of boll number (Fig. 6), boll weight (Fig. 7), and lint yield observed in the mapping assessment were substantially lower than those recorded at the plot level, since the mapping analysis was performed separately for each combination of plant third and reproductive position. Therefore, unlike the plot-level assessment, which represents the total number of bolls per unit area, mapping expresses only the fraction of this production associated with each stratum of the plant architecture, resulting in numerically lower values.

Plant mapping showed that the VR_1 treatment had an average number of bolls per m² that was 24.8% higher than that observed in the Fixed treatment (Fig. 6). This result suggests that VR_1 management favored the initiation and/or retention of reproductive structures in the evaluated plants, reflecting a modification in the pattern of boll distribution within the plant architecture. Although this difference was not detected in the assessment of total boll number at the plot level, this indicates that the changes observed in the mapping assessment, because they were derived from a plot subsample, were not sufficiently expressive to be reflected in the integrated plot-level result. However, because this response represents only a trend, it should be interpreted with caution, since the p-value was not lower than 0.05.

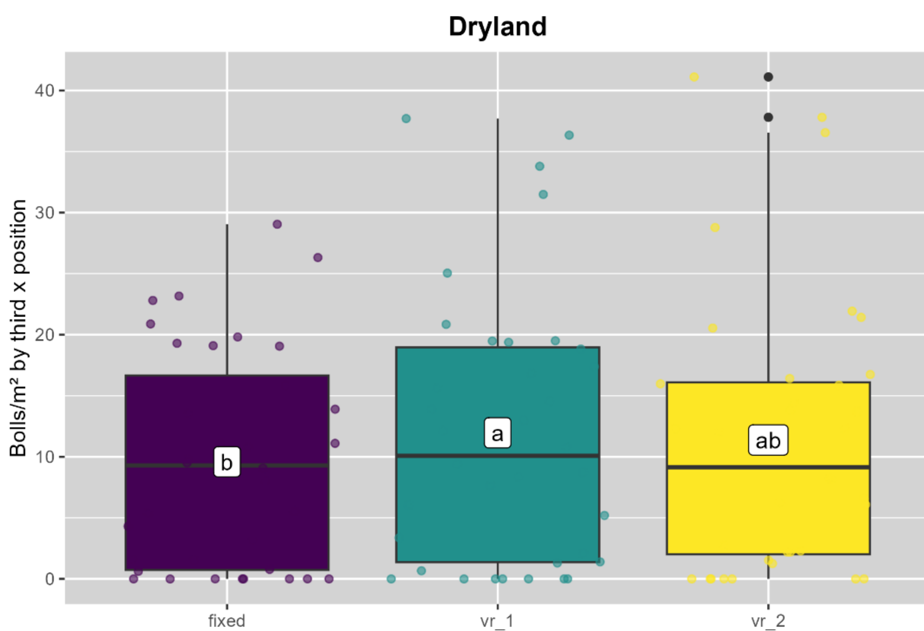

Fig. 6 Number of bolls per m² according to treatments within plant mapping, at the 5% probability level

Under dryland conditions, the Fixed treatment showed greater average boll weight compared with the VR_1 and VR_2 treatments. Considering the values observed in the mapping assessment, average boll weight in the Fixed treatment (2.95 g) was 112.2% higher than in VR_1 (1.39 g) and 49.0% higher than in VR_2 (1.98 g). The greater average boll weight observed in the Fixed treatment was probably associated with the lower number of bolls per unit area, suggesting lower intra-plant competition for photoassimilates among reproductive structures. Under conditions of lower boll load, the relative availability of carbohydrates per structure tends to be greater, which may favor boll filling and biomass accumulation in each remaining boll. In contrast, VR_2 showed lighter bolls, which may be explained by the greater number of bolls, a condition in which the simultaneous demand for assimilates is higher and competition among reproductive structures tends to intensify, reducing the amount of resources available for individual boll filling. These results reinforce the existence of a compensatory mechanism among yield components, in which an increase in boll number may be associated with a reduction in individual boll weight, whereas a lower reproductive load may favor the formation of heavier bolls. Under irrigated conditions, the Fixed treatment also showed greater average boll weight than VR_1, being 32.6% higher (Fig. 7).

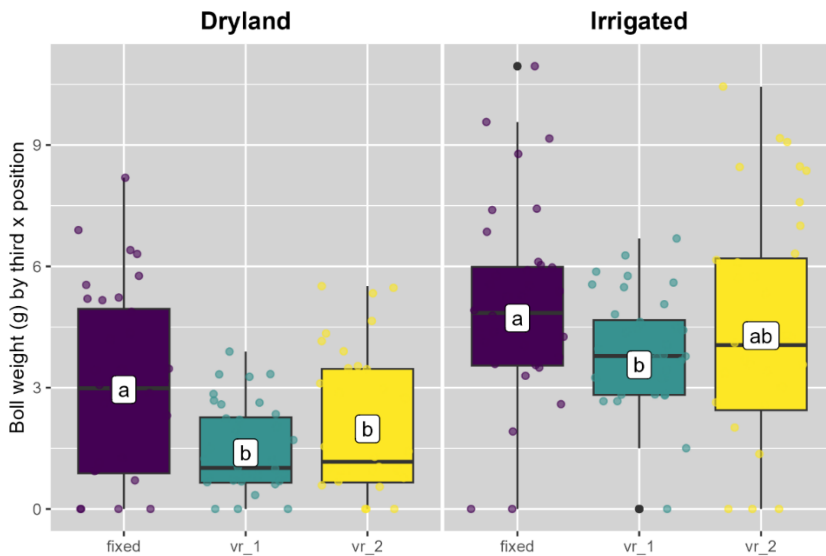

Fig. 7 Mean boll weight within plant thirds and fruiting positions, according to treatments (fixed, VR_1, and VR_2) under two production systems (dryland and irrigated), at the 5% probability level

Boll weight was influenced by the interaction between plant third and boll position. In both environments, the lower and middle thirds showed less variation among positions, whereas in the upper third there was a reduction in boll weight at the more distal positions. Position 1 in the upper third showed greater boll weight, while positions 2 and 3+ showed the lowest values, especially position 3+. These results indicate that the reduction in boll weight occurred mainly in bolls located at the more distal positions of the upper third of the plant (Fig. 8).

The lower boll weight observed in the more distal positions and in the upper third may be related to the timing of formation and the period available for filling these structures. Boll filling is a relatively long process, requiring approximately 40 days for much of the mass to be accumulated (Thornley & Hesketh, 1972). Thus, bolls located in the first positions of the fruiting branches, especially in the lower and middle thirds, tend to be formed earlier and have more time to accumulate mass.In contrast, bolls located in more external positions or in the upper third are formed later, when the plant already has other developing fruits. As a result, these structures may face greater competition for assimilates and a shorter effective filling period, resulting in lower average boll weight. This behavior helps explain the reduction in boll weight at positions 2 and 3+ in the upper third (Pabuayon et al., 2021).

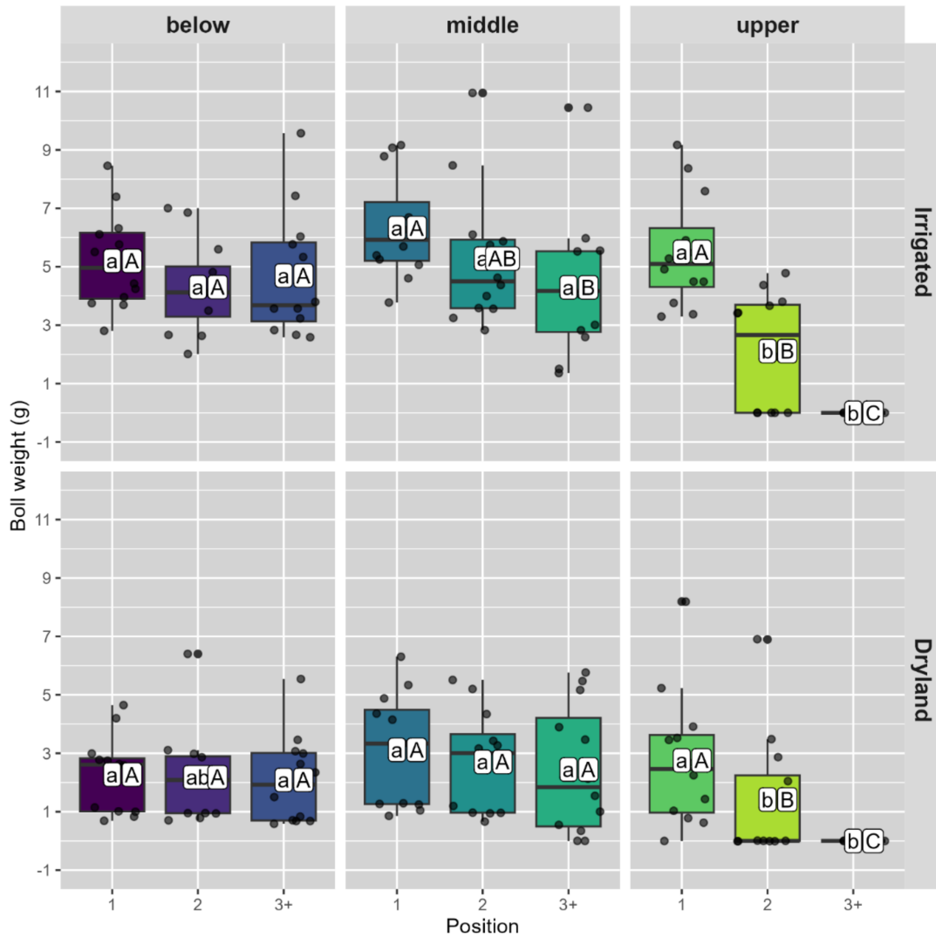

Fig. 8 Boll weight (g) according to plant third (below, middle, and upper) and fruiting position (1, 2, 3+) under two production systems (irrigated and dryland). Uppercase letters compare positions within each plant third, and lowercase letters compare plant thirds within each position, at the 1% probability level

In both environments, irrigated and dryland, there was a greater concentration of bolls in the positions closest to the main stem, especially position 1. In the lower and middle thirds, boll number was greater at position 1, followed by position 2, while position 3+ showed the lowest values. In the upper third, boll number was reduced compared with the lower and middle thirds, especially at positions 2 and 3+, which showed values close to zero in both environments. This pattern indicates that boll production was mainly concentrated in the proximal positions of the lower and middle thirds of the plant. The results demonstrate that boll distribution within the plant was uneven, with greater contribution from positions 1 and 2 in the lower and middle thirds, whereas the upper third, especially at the more distal positions, showed low contribution to total boll number (Fig. 9). This pattern may be associated with the dynamics of formation and retention of reproductive structures in cotton. Similar to what was observed for boll weight, structures located in more distal positions and in the upper third are formed later, when the plant already has a greater established reproductive load. Under this condition, competition for assimilates tends to be higher, which may favor abscission or reduce fruit retention. Thus, the lower number of bolls at positions 2 and 3+ in the upper third suggests a lower probability of maintaining these structures until harvest, resulting in a low contribution to total boll number m^{-2} (Schaefer et al., 2017; Pabuayon et al., 2021).

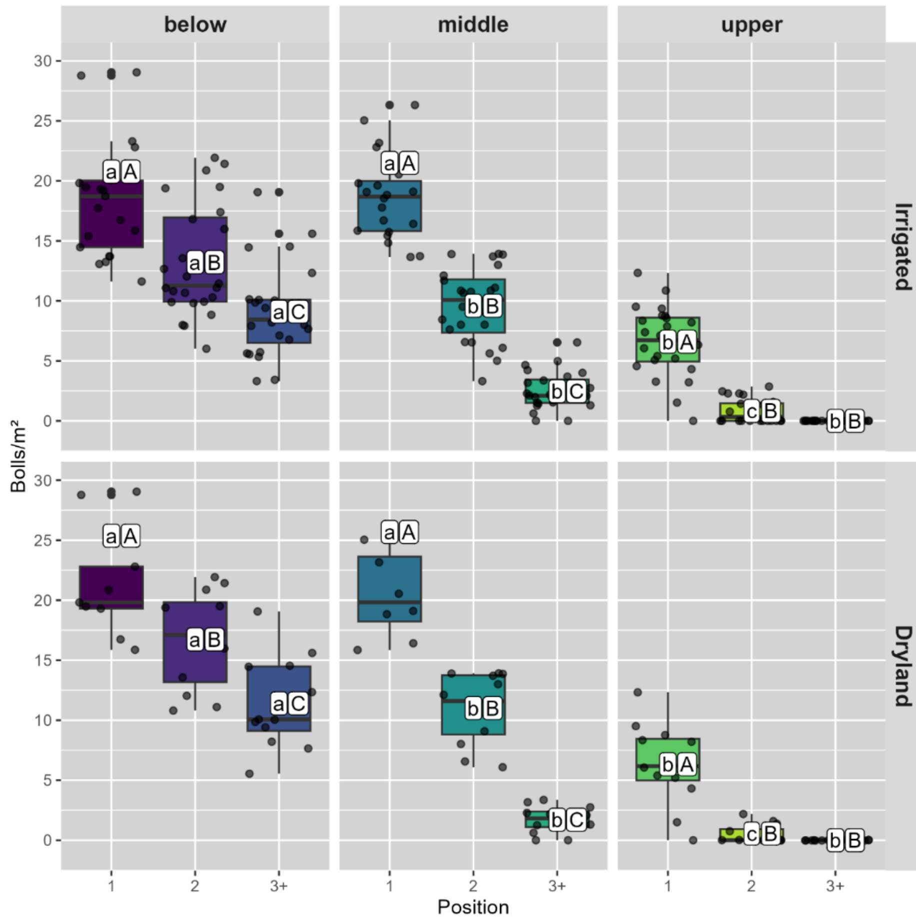

Fig. 9 Bolls (m^2) according to plant third (below, middle, and upper) and fruiting position (1, 2, 3+) under two production systems (irrigated and dryland). Uppercase letters compare positions within each plant third, and lowercase letters compare plant thirds within each position, at the 1% probability level

Lint yield distribution showed a pattern similar to that observed for the number of bolls m^{-2}, with higher values in the proximal positions of the middle and lower thirds of the plant. Although average boll weight also varied among thirds and positions, this variation was less expressive, suggesting a smaller contribution to the differences observed in yield. This behavior is consistent with Sharma et al. (2015), who reported a greater influence of boll number than boll weight on cotton yield. In both environments, the middle and lower thirds, especially at position 1, showed the greatest contributions to lint yield. Yield decreased at the more distal positions, mainly at position 3+, and was low in the upper third, especially at positions 2 and 3+. These results indicate that fiber production was concentrated in the more proximal reproductive structures of the plant (Fig. 10).

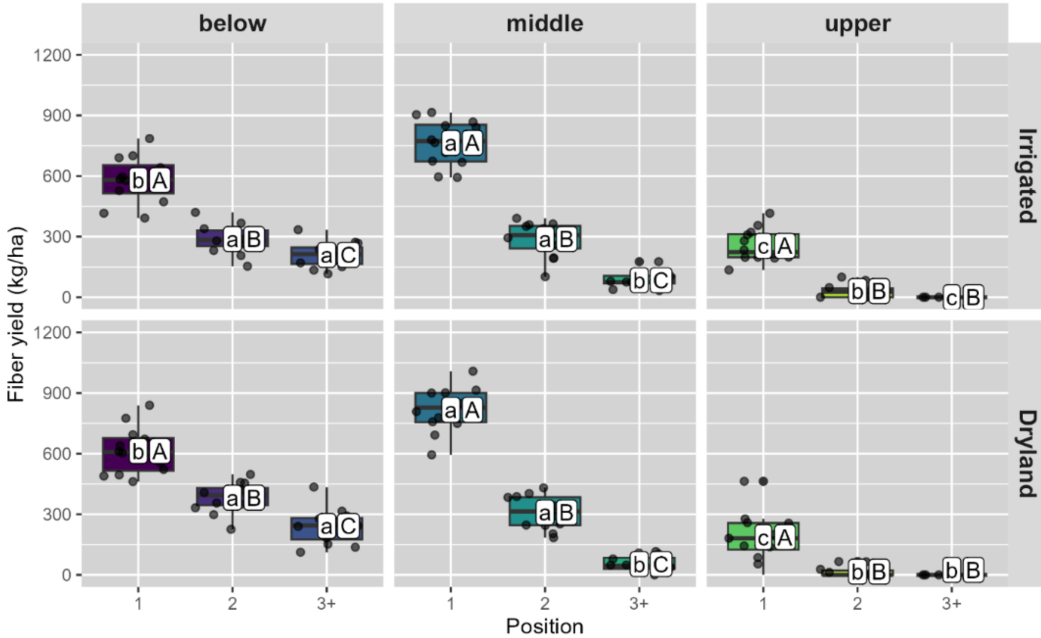

Fig. 10 Fiber yield values (kg ha⁻¹) according to plant third (below, middle, and upper) and fruiting position (1, 2, 3+) under two production systems (irrigated and dryland). Uppercase letters compare positions within each plant third, and lowercase letters compare plant thirds within each position, at the 1% probability level

Conclusion

In conclusion, LiDAR estimated plant height with high precision ($R^2 = 0.97$), while the combination of multispectral imagery, elevation data, and meteorological information allowed cotton node number to be predicted, demonstrating the potential of sensors to support variable-rate plant growth regulator recommendations and reduce dependence on manual assessments. The VR_2 treatment showed greater lint yield under dryland conditions, possibly due to better adjustment of application timing to environmental conditions, whereas plant growth regulator management had limited effects on fiber quality, with changes observed only for the yellowness index (+b). At the plant level, yield and yield components were influenced by the interaction between plant third and boll position, with greater contribution from the proximal positions of the middle and lower thirds and lower participation of the distal positions and the upper third.

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