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Cotton lint yield responses to nitrogen fertilization are diverse in South Carolina

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Abstract

Optimizing nitrogen (N) management in cotton (*Gossypium hirsutum* L.) production across diverse environments in the southeastern United States remains a challenge. We examined cotton yield responses to N fertilization on multiple commercial farms with different management histories in four physiographic regions of South Carolina. Field experiments were conducted using a randomized complete block design with four N rates (0, 45, 90, and 135 kg ha⁻¹) replicated three times at 50 trials from 2021 to 2023. Field management varied by previous crop, type of tillage, water regime, and history of conservation practices. Cotton lint yield was responsive to N fertilization in 52% of the trials. Economic optimum N rate (EONR) had an interquartile range of 0–135 kg ha⁻¹, with 68% of trials having values <78 kg ha⁻¹ (below the recommended rate). The physiographic region influenced EONR ($p < 0.05$), with higher EONR values at Coastal Plains and Sandhills compared to the Piedmont region, reflecting differences in soil types and the history of management. Sites with long-term conservation practices had greater yield without N input, higher relative yields, and lower N factor (fertilizer N required per unit of lint) than conventionally managed sites. These sites exhibited greater residual soil N content, thereby reducing N fertilizer requirements. Current-season management had varying impacts, and tillage primarily influenced how efficiently cotton used N (affecting EONR and N factor), while water regime affected yield potential indices (control, maximum, and profit-maximizing yield) as well as EONR. These findings emphasize the need for site-specific N recommendations that should consider physiographic characteristics, current-season management practices, and the long-term history of conservation practices. This study provides a foundation for developing more sustainable and efficient N management practices for cotton production.

Abbreviations: BD, bulk density; CC-L, long-term cover crops; EONR, economic optimum nitrogen rate; NCP, no conservation practice; Nf, nitrogen factor; NL, non-linear; PL, poultry litter; PMY, profit-maximizing yield; RSA, residual soil ammonium-N content; RSN, Residual soil nitrate-N content; RY, relative yield.

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Plain Language Summary

Cotton farmers need to know how much nitrogen (N) fertilizer to apply for best yields while protecting the environment, so we conducted 50 on-farm trials across South Carolina from 2021 to 2023 to find the right amount for different soils and farming practices. The study included four N rates (0, 45, 90, and 135 kg ha⁻¹) in fields with different soils, climates, and management histories. Note that 52% of trials responded to N, but the optimum rate varied from 0 to 135 kg ha⁻¹. Fields in the sandy Coastal Plain and Sandhills regions needed more nitrogen than clay-rich Piedmont soils. Farms using cover crops or poultry litter for years produced more cotton without additional or minimal N fertilizer. Current recommendations of 78–112 kg ha⁻¹ are too high—68% of fields needed less than 78 kg ha⁻¹. This research shows farmers should adjust N rates based on their location and farming history rather than using uniform rates across regions.

1 | INTRODUCTION

Nitrogen (N) is one of the most essential nutrients required for the growth and profitability of cotton. An optimum amount of N application is critical to ensure good growth for maximizing environmental potential, to avoid rank growth devoid of fruiting structures, and to minimize environmental losses of N (Chen et al., 2019; Gardner & Tucker, 1967; Singh & Craswell, 2021; Sui et al., 2017). Current N application recommendations for cotton production are based on yield goals (Miley & Oosterhuis, 1990) derived from state-specific studies. In South Carolina, Oklahoma, Tennessee, Mississippi, and Arkansas, the recommended N rate ranges from 56 to 112 kg ha⁻¹ for a yield goal of 538–1076 kg ha⁻¹ (i.e., 1–2 bales acre⁻¹) with adjustments based on residual soil nitrate-N, previous crop and/or soil texture (Adotey et al., 2021; Arnall & Boman, 2017; Jones et al., 2023; McConnell & Kirst, 2000; Oldham & Dodds, 2017). Besides these factors, improved agricultural management practices and newly developed cotton varieties may play a role in the optimum N required by the crop and made available in the soil. Region- and management-specific studies to evaluate the effects of crop rotation, conservation practices, and physiographic characteristics on cotton growth and yield responses could help improve N fertilizer recommendations.

The direct and indirect effects of management and conservation practices on cotton yield have been studied before. For example, crop rotation practices were shown to improve soil health (Karlen et al., 2006), nutrient cycling (Grant et al., 2002), water use efficiency (Tennakoon & Hulugalle, 2006), and weed and pest control (Zohry & Ouda, 2018). The N fertilizer recommendation for cotton following a legume previous crop can be reduced by 28 kg ha⁻¹ in South Carolina (Jones et al., 2023). Cotton yield increased by 10%–32% under cotton–corn (*Zea mays* L.) rotation compared with

continuous cotton due to increased soil organic carbon and microbial activity (Reddy et al., 2006). However, cotton lint yield was not different between sorghum (*Sorghum bicolor* L. Moench)–cotton rotation and continuous cotton (Booker et al., 2007).

Cover crops can improve soil health by providing surface residues that protect the soil from erosion (De Baets et al., 2011; Hoorman, 2009). Conservation practices can lead to better synchronization between crop N demand and soil N supply, potentially reducing N losses to the environment (Alam et al., 2020). Cover crops have been shown to increase lint yield by 5% and reduce weed biomass by 20% (Toler et al., 2019). The type of cover crop species may be an essential aspect of N availability in soil, as Toler et al. (2019) mentioned that overall leguminous cover crops can increase seed cotton yield by 17%–43%.

Tillage management may also have a significant effect on cotton yield. Greater lint yield under no-tillage with terminated wheat cover crop compared to conventional or strip-till was observed in Texas (DeLaune et al., 2020). No-tillage had similar or greater yields than surface-tillage, whether managed with inorganic N fertilizer input or with leguminous cover crops in Louisiana (Boquet et al., 2004). No-tillage produced yields comparable to those of conventional tillage with a rye cover crop in silty clay soils of Tennessee (Schwab et al., 2002). These studies suggest the importance of understanding the effects of controlled management practices on cotton yield response to N application.

Geographic location is another critical factor influencing cotton yield response to N application. Sites across diverse physiographic regions offer unique growing conditions with varied soil and climatic conditions. The Flatwoods, Coastal Plain, Sandhills, and Piedmont regions in South Carolina encompass a broad spectrum of soil types, from loamy sands to clay loams. Soil and climatic variations create a

complex landscape for N management. Such diverse conditions present an opportunity to develop more precise site-specific N management strategies that could improve upon traditional yield-goal-based recommendations.

Addressing the complexity of N management across these diverse conditions requires an approach that integrates economic considerations with site-specific factors. The relationship between management practices and lint yield is crucial, considering that economics is essential for N fertilizer recommendations (Franzluebbers, 2018). The economic optimum N rate (EONR) defines the amount of N required for profit-maximizing yield (PMY), which is calculated to balance the cost of N fertilizer against the value of increased cotton lint yield. Extensive field trials are necessary to determine N production functions for specific areas, and then an EONR can be calculated for specific production environments. Apart from fluctuations in N fertilizer and lint prices, soil texture (Alotaibi et al., 2018) and weather conditions (Wang et al., 2020) may significantly influence EONR.

Given the challenges of N management in cotton production across diverse conditions, this study aimed to refine and improve N recommendations for cotton in South Carolina. The primary objective was to determine cotton lint yield response to N application across a diversity of sites, varying by conservation history, previous crop, tillage management, and water regime. We hypothesized that cotton produced in fields with conservation management would have unique N production functions and lower EONR compared to conventionally managed fields. Specifically, we expected long-term conservation practices history, leguminous previous crops, and no-tillage to lower EONR compared with no conservation history, continuous cotton, and conventional tillage.

2 | MATERIALS AND METHODS

2.1 | Study design and site characteristics

A series of N-rate response trials was conducted across South Carolina from 2021 to 2023. A total of 50 trials were conducted with 17 cotton producers in 14 counties, representing a diversity of cotton production landscapes in South Carolina. Study sites represented 19 different soil series across four physiographic regions: Coastal Plain (30), Flatwoods (9), Sandhills (6), and Piedmont (5) (USDA-NRCS ArcGIS Online, 2025).

Sites varied in current-season management practices and were sorted into categories of tillage management (41 strip-till and 9 no-till), water regime (15 irrigated and 35 dryland), previous crop (22 cotton, 13 corn, and 15 legumes, including soybean [*Glycine max* L.] and peanut [*Arachis hypogaea* L.]), and history of conservation management. Conservation management categories included short-term cover crops (CC-

S, <5 years, five sites), medium-term cover crops (CC-M, 5–10 years, 11 sites), and long-term cover crops (CC-L, >10 years, 15 sites), poultry litter (PL) application (nine sites), and no conservation practice (NCP, 10 sites). Information about the location, soil series, management practices, physiographic region, history of conservation practices, cotton variety, and residual soil nitrate-N (RSN) and ammonium-N (RSA) content for each site is presented in Table 1.

A randomized complete block design with three replications of four N rates (0, 45, 90, and 135 kg ha⁻¹) was implemented at each site. All sites in 2022 and 2023 had plot widths from 3 to 4 m, depending on the row width used by the cooperating farmer, and a plot length of 7.6 m. In 2021, the plot width ranged from 4 to 12 m, and the plot length varied from 30 to 120 m. Nitrogen treatments were applied as urea (46-0-0) using a handheld broadcast spreader 30–45 days after planting. The entire experimental area received 67 kg K₂O ha⁻¹ as KCl fertilizer, applied simultaneously with the N treatments to ensure that potassium (K) deficiency did not confound the experimental results, especially given the common K deficiency in sandy, low organic carbon (C), and low cation exchange capacity soils of the Southern Coastal Plain (Mitchell & Huluka, 2016). Phosphorus (P) fertilizer was not applied at any site since soil-test phosphorus prior to fertilization was >78 mg kg⁻¹ at all sites, indicating a sufficient level of P in soil for cotton production (Cox & Barnes, 2002; Crozier et al., 2004, 2010).

2.2 | Soil sampling and analysis

Baseline soil samples were collected after cotton emergence but before fertilizer application from each site to determine pre-treatment RSN and RSA contents. From each replication, eight soil cores (0- to 10-cm depth) were composited, while four cores were composited from 10- to 30-cm and 30- to 60-cm depths. The collected samples were oven-dried at 50–55°C for 48 h or until constant weight was achieved. Samples were ground and passed through a 2-mm sieve.

A 10 g subsample of soil was extracted with 20 mL of 2 M KCl by shaking for 30 min on a reciprocating shaker at 180 oscillations per minute, then filtered through grade 360 qualitative filter paper. The extracts were analyzed for ammonium-N concentration using the salicylate-nitroprusside method and for nitrate-N concentration using the hydrazine reduction method on an automated analyzer (Auto-Analyzer 3, Seal Analytical, Inc.) following standard protocols (Franzluebbers et al., 2021). To convert RSN and RSA concentrations to content values, bulk density (BD; Mg m⁻³) at each depth increment (0–10, 10–30, and 30–60 cm) was estimated from total organic carbon (TOC; g kg⁻¹) determined by dry combustion analysis (Franzluebbers, 2024; detailed soil characterization data to be presented

TABLE 1 Characterization of 50 cotton experiment sites across South Carolina's physiographic regions (2021–2023) showing location details, soil classification, water regime (WR), tillage practices (T), previous crop (PC), history of conservation practices (HCP), and cotton varieties used for N rate response trials. Pre-treatment residual soil nitrate-N (RSN; kg ha⁻¹) and ammonium-N content (RSA; kg ha⁻¹) at 0- to 10-cm and 0- to 60-cm depths are presented for each site.

Site	County	Soil taxonomy and series	WR	T	PC	HCP	Variety	RSN _{0–10 cm}	RSA _{0–10 cm}	RSN _{0–60 cm}	RSA _{0–60 cm}
Flatwoods											
A	Hampton	Aquic Paleudults; Goldsboro loamy sand	D	NT	Cotton	NCP	DP 2038B3XF	4	7	10	48
N1	Colleton	Lamellic Quartzipsamments; Alpin fine sand	D	ST	Corn	CC-S	DP 2055B3XF	6	6	15	56
N2	Colleton	Lamellic Quartzipsamments; Alpin fine sand	D	ST	Corn	NCP	DP 2055B3XF	5	5	12	55
Q1	Georgetown	Aeric Endoaquults; Yauhannah loamy fine sand	D	ST	Corn	PL	ST 5091B3XF	35	24	63	107
Q2	Georgetown	Aeric Endoaquults; Yauhannah loamy fine sand	D	ST	Corn	PL	ST 5091B3XF	24	18	46	81
R1	Berkeley	Aquic Hapludults; Duplin fine sandy loam	D	ST	Corn	CC-S	NG 5150B3XF	25	6	60	51
R2	Berkeley	Aquic Hapludults; Duplin fine sandy loam	D	ST	Corn	CC-S	NG 5150B3XF	22	7	65	48
S1	Orangeburg	Aeric Paleaquults; Lynchburg fine sandy loam	D	ST	Cotton	CC-L	NG 4939B3XF	14	26	23	68
S2	Orangeburg	Aeric Paleaquults; Lynchburg fine sandy loam	D	ST	Cotton	CC-L	NG 4939B3XF	12	24	33	93
Coastal Plain											
B	Calhoun	Plinthic Kandiudults; Suffolk loamy sand	D	ST	Legume	CC-M	NA	11	7	30	25
C	Calhoun	Typic Hapludults; Suffolk loamy sand	I	ST	Legume	CC-M	NA	15	7	35	35
D	Orangeburg	Arenic Kandiudults; Fuquay sand	I	ST	Legume	PL	DP 2055B3XF	41	7	93	60
E	Orangeburg	Arenic Kandiudults; Fuquay sand	I	ST	Legume	PL	DP 2055B3XF	53	13	121	94
F	Allendale	Arenic Kanhapludults; Uchee sand	I	ST	Cotton	CC-M	DP 2015	2	3	8	35
J	Orangeburg	Arenic Paleudults; Goldsboro sandy loam	D	ST	Legume	CC-L	DP 2055B3XF	10	8	21	39
K	Orangeburg	Aquic Paleudults; Goldsboro sandy loam	D	ST	Legume	NCP	DP 2055B3XF	6	7	11	44

(Continues)

TABLE 1 (Continued)

Site	County	Soil taxonomy and series	WR	T	PC	HCP	Variety	RSN _{0–10 cm}	RSA _{0–10 cm}	RSN _{0–60 cm}	RSA _{0–60 cm}
L	Marlboro	Typic Kandiudults; Norfolk loamy sand	D	ST	Legume	CC-M	DP 2127B3XF	17	16	76	140
M	Marlboro	Oxyaquic Paleudults; Norfolk loamy sand	D	ST	Corn	CC-M	DP 1646B2XF	28	17	120	200
O1	Allendale	Typic Hapludults; Emporia loamy sand	I	ST	Cotton	CC-M	DP 2015	5	5	28	68
O2	Allendale	Typic Hapludults; Emporia loamy sand	I	ST	Cotton	CC-M	DP 2015	8	5	32	55
OA	Allendale	Typic Hapludults; Emporia loamy sand	I	ST	Cotton	CC-M	DP2127B3XF	17	22	62	66
OB	Allendale	Typic Hapludults; Emporia loamy sand	I	ST	Cotton	CC-M	DP 2127B3XF	7	7	23	38
T1	Allendale	Typic Kandiudults; Norfolk loamy sand	I	ST	Legume	CC-L	NG 3195B3XF	24	5	85	26
T2	Allendale	Typic Kandiudults; Norfolk loamy sand	I	ST	Legume	CC-L	NG 3195B3XF	19	4	56	23
TA	Allendale	Typic Kandiudults; Norfolk loamy sand	I	ST	Legume	CC-L	NG 3195B3XF	12	24	59	49
TB	Allendale	Typic Kandiudults; Norfolk loamy sand	I	ST	Legume	CC-L	NG 3195B3XF	9	11	44	38
U1	Marlboro	Typic Kandiudults; Norfolk loamy sand	D	ST	Corn	CC-L	ST 5091B3XF	8	6	17	33
U2	Marlboro	Typic Kandiudults; Norfolk loamy sand	D	ST	Legume	NCP	ST 50913XF	13	4	37	27
UA	Marlboro	Typic Kandiudults; Norfolk loamy sand	D	ST	Cotton	CC-L	ST 5091B3XF	24	10	78	44
UB	Marlboro	Typic Hapludults; Norfolk loamy sand	D	ST	Cotton	NCP	ST 5091B3XF	16	10	58	44
V	Marlboro	Typic Kandiudults; Norfolk loamy sand	D	ST	Corn	CC-L	DP 2141NRB3XF	30	9	67	64
VA	Marlboro	Typic Paleudults; Norfolk loamy sand	D	ST	Corn	CC-L	DP 2127B3XF	24	9	137	47
VB	Marlboro	Aquic Paleudults; Norfolk loamy sand	D	ST	Corn	CC-L	DP 2038B3XF	12	8	85	37
W1	Barnwell	Arenic Kandiudults; Wagram sand	I	ST	Cotton	NCP	NG 3195B3XF	7	4	14	28
W2	Barnwell	Arenic Kandiudults; Wagram sand	I	ST	Cotton	NCP	NG 3195B3XF	11	5	18	22
X	Dillon	Plinthic Kandiudults; Dothan loamy fine sand	D	NT	Cotton	CC-L	PHY 443W3FE	23	10	38	38
XA	Dillon	Typic Kandiudults; Orangeburg loamy sand	D	NT	Legume	CC-L	PHY 411W3FE	19	14	86	47
XB	Dillon	Typic Paleudults; Faceville loamy fine sand	D	NT	Legume	CC-L	PHY 411W3FE	20	10	78	53

(Continues)

TABLE 1 (Continued)

Site	County	Soil taxonomy and series	WR	T	PC	HCP	Variety	RSN _{0–10 cm}	RSA _{0–10 cm}	RSN _{0–60 cm}	RSA _{0–60 cm}
Z	Darlington	Typic Kandiudults; Norfolk loamy sand	D	ST	Corn	NCP	DP 1646B2XF	22	4	38	39
Sandhills											
G	Aiken	Plinthic Kandiudults; Dothan loamy sand	D	ST	Cotton	NCP	NG 5711B3XF	30	5	66	34
H	Aiken	Grossarenic Kandiudults; Troup sand and Vaucluse-Ailey complex	D	ST	Legume	CC-M	DP 1840B2XF	49	8	112	53
I	Aiken	Fragic Kanhapludults; Troup sand and Vaucluse-Ailey complex	I	ST	Corn	CC-M	DP 2155B3XF	29	11	66	36
P1	Aiken	Plinthic Kandiudults; Dothan loamy sand	D	ST	Cotton	CC-S	NG 4190B3XF	12	9	28	39
P2	Aiken	Plinthic Kandiudults; Dothan loamy sand	D	ST	Cotton	NCP	NG 4190B3XF	8	7	28	31
PA	Aiken	Plinthic Kandiudults; Dothan loamy sand	D	ST	Cotton	CC-S	DP 2141NRB3XF	6	13	27	41
Piedmont											
YA	York	Ultic Hapludalfs; Mecklenburg-Wynott complex	D	NT	Cotton	PL	DP 2115B3XF	37	12	120	59
YC1	Chester	Oxyaquic Vertic Hapludalfs; Iredell fine sandy loam	D	NT	Cotton	PL	DP 2239B3XF	34	7	75	41
YC2	Chester	Oxyaquic Vertic Hapludalfs; Iredell fine sandy loam	D	NT	Cotton	PL	DP 2239B3XF	12	6	32	35
YK1	York	Ultic Hapludalfs; Mecklenburg-Wynott complex,	D	NT	Cotton	PL	DP 2115B3XF	29	8	57	47
YK2	York	Ultic Hapludalfs; Mecklenburg-Wynott complex,	D	NT	Cotton	PL	DP 2115B3XF	31	10	54	41

Note: WR: Water Regime (I: Irrigated, D: Dryland); T: Tillage (NT: No-till, ST: Strip-till); HCP: History of conservation practice (PL: Poultry litter, NCP: No conservation practice, CC: Cover crops with duration—Short: <5 years [CC-S], Medium: 5–10 years [CC-M], Long: >10 years [CC-L]).

elsewhere) using the pedotransfer function in Equation (1) (Franzluebbers, 2024):

$$BD = 1.71 \times e^{(-0.013 \times TOC)} \quad (1)$$

Cumulative RSN and RSA contents (kg ha^{-1}) across the 0–60 cm profile were calculated by summing the content from each depth increment using Equations (2) and (3), respectively:

$$\begin{aligned} RSN_{0-60 \text{ cm}} = & (1 \times BD_{0-10 \text{ cm}} \times RSN_{0-10 \text{ cm}}) \\ & + (2 \times BD_{10-30 \text{ cm}} \times RSN_{10-30 \text{ cm}}) \\ & + (3 \times BD_{30-60 \text{ cm}} \times RSN_{30-60 \text{ cm}}) \quad (2) \end{aligned}$$

$$\begin{aligned} RSA_{0-60 \text{ cm}} = & (1 \times BD_{0-10 \text{ cm}} \times RSA_{0-10 \text{ cm}}) \\ & + (2 \times BD_{10-30 \text{ cm}} \times RSA_{10-30 \text{ cm}}) \\ & + (3 \times BD_{30-60 \text{ cm}} \times RSA_{30-60 \text{ cm}}) \quad (3) \end{aligned}$$

where $RSN_{0-60 \text{ cm}}$ and $RSA_{0-60 \text{ cm}}$ are cumulative profile contents (kg ha^{-1}), subscripted variables ($BD_{0-10 \text{ cm}}$, $RSN_{0-10 \text{ cm}}$, $RSA_{0-10 \text{ cm}}$, etc.) represent BD (Mg m^{-3}) and concentrations (mg kg^{-1}) at specific depth intervals, and coefficients (1, 2, and 3) are conversion factors for each depth increment ($\text{cm depth}/10$).

2.3 | Cotton harvest data collection

Cotton was handpicked from 1.5 m of the two middle rows at physiological maturity. Seed cotton was weighed and reported as kg ha^{-1} seed yield. Lint yield was calculated from the gin turnout after ginning seed cotton using a laboratory 10-saw gin (Continental Gin) to separate lint and seed.

2.4 | Calculations and statistical analyses

Lint yield responses to N application rates were tested using a hierarchy of relevant functions (Franzluebbers, 2018). First, if data fit a nonlinear (NL) function described in Equation (4), then they were selected as most agronomically appropriate. The model was fitted using the Levenberg–Marquardt algorithm (nlsLM function, minpack.lm package in R) with initial parameters: Y_0 = mean yield at zero N application rate, A (maximum yield- Y_0), and $B = 0.02$. The exponential model was accepted if (i) $A > 0$, (ii) B was between 0.001 and 0.15, and (iii) the percent yield increase from Y_0 to maximum yield was $\geq 3\%$. If the exponential model failed to meet these criteria, then a simple linear regression was used (Equation 5). However, if the linear regression had a negative slope,

then mean yield across N rates was calculated to assume no response to N input (Franzluebbers, 2018). The sites were categorized as exponential, linear, and mean fit, according to the best-fitting models:

$$\text{Exponential model : } Y = Y_0 + A \times (1 - \exp(-B \times N)) \quad (4)$$

$$\text{Linear model : } Y = Y_0 + B \times N \quad (5)$$

where Equations (4) and (5) include Y as lint yield (kg ha^{-1}), Y_0 as lint yield (kg ha^{-1}) at no N application, B as the change in Y per unit change in N (slope), and N as N rate applied (kg ha^{-1}). In addition, Equation (4) includes A as the additional yield potential (kg ha^{-1}) with limitless N input. Best-fit regression models were used to obtain the coefficient of determination (r^2) from the 12 observations (four N rates and three replications).

EONR was calculated by isolating the N rate that produced maximum profit from Equation (6). The yield at this N rate was PMY:

$$\text{Profit} = (\text{Lint yield} \times \text{Lint price}) - (N \text{ applied} \times N \text{ price}) \quad (6)$$

Sites with 0 kg ha^{-1} EONR were considered nonresponsive sites. Costs of seeds, pesticides, and fertilizer other than N were considered constant for calculating maximum profit. The commodity value of $\$1.65 \text{ kg}^{-1}$ lint was the average received by producers in the southeast during the 2022–2024 marketing year (USDA-AMS, 2025a). Nitrogen cost of $\$1.98 \text{ kg}^{-1}$ was the average paid by producers based on the USDA South Carolina crop production report (USDA-AMS, 2025b).

After selecting the best-fit model among the NL, linear, and mean regressions, unfertilized yield (Y_0) and maximum yield (Y_{MAX}) were calculated from the regression for each site. Relative yield (RY) was calculated as the ratio of Y_0 to Y_{MAX} for each site, expressed as a percentage (Pearce et al., 2022):

$$\text{Relative yield (\%)} = \frac{Y_0}{Y_{\text{MAX}}} \times 100 \quad (7)$$

The N factor (Nf) was calculated from EONR needed to achieve PMY according to:

$$\text{N factor (kg N kg}^{-1} \text{ lint)} = \frac{\text{EONR}}{\text{PMY}} \quad (8)$$

Weather data were collected from the NOWData-NOAA, based on the nearest NOAA weather station (NWS-NOAA, 2023). All analyses for selecting the best-fit model were conducted using R statistical software (version 4.5.1). The results were organized using MS Excel version 16.86. Statistical software JMP Pro 16.0 (SAS Institute Inc.) was used to calculate the mean and range for yield parameters, RSN, and RSA.

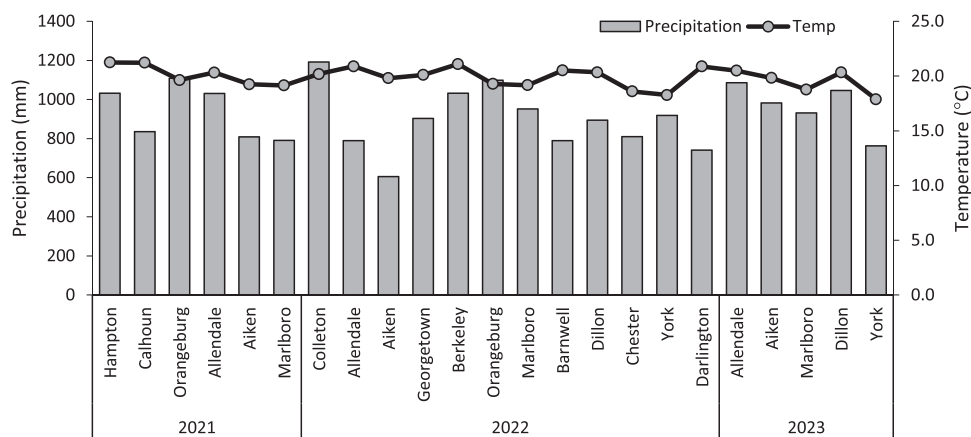


FIGURE 1 Total precipitation (mm) and mean temperature (°C) of each county for the growing cotton season (April–December) with test sites from 2021 to 2023. Vertical bars represent total precipitation, and the line shows the mean temperature.

The Kruskal–Wallis test is a nonparametric statistical method used to evaluate differences among three or more independent groups based on a single continuous variable that does not follow a normal distribution (Kruskal & Wallis, 1952). This test was used to separate the influences of previous crops, tillage, water regime, physiographic regions, and conservation practices on Y_0 , Y_{MAX} , RY, EONR, PMY, Nf, RSN, and RSA. Regression analyses were conducted to evaluate the relationships between RSN and RSA at both 0- to 10-cm and 0- to 60-cm depths and RY and EONR. The significant models with the highest r^2 were selected.

3 | RESULTS

3.1 | Temperature and precipitation

The long-term (2000–2024) mean annual temperature was 18°C, and the mean annual precipitation was 1132 mm (data not shown) across the study region (NWS-NOAA, 2023). During the 2021–2023 study period, the mean annual temperature was 17.5°C, while the mean temperature during the growing season was 19.9°C. The mean cotton-growing season (April–December) temperature for 2021, 2022, and 2023 was 20.1, 19.9, and 19.5°C, respectively. The lowest mean temperature was in York County in both 2022 (18.3°C) and 2023 (17.9°C), while the highest mean temperature was in Hampton County in 2021 (21.2°C; Figure 1).

Total precipitation during the growing season (April–December) averaged 919 mm across all sites during 2021–2023, while the mean precipitation for the whole year was 1241 mm. Maximum growing-season precipitation of 1192 mm was recorded in Colleton County in 2022, while a minimum of 605 mm was recorded in Aiken County in 2022. Mean growing-season precipitation for 2021, 2022, and 2023 was 935, 894, and 962 mm, respectively. Among

physiographic regions, Flatwoods had the highest mean daily temperature (18.0°C) and annual precipitation (1341 mm), followed by Coastal Plain (17.7°C and 1283 mm) and Sandhills (17.1°C and 1085 mm), while lowest were in Piedmont (15.8°C and 1132 mm). Annual precipitation and mean temperature during the growing season had no significant association with cotton lint yield (data not shown).

3.2 | Lint yield response to N application

Lint yield responses to N application rates varied widely among the 50 trials from 2021 to 2023 (Table 2). Lint yield without N application (Y_0) ranged from 272 to 1992 kg ha⁻¹, with a mean of 1100 kg ha⁻¹. The type and occurrence of lint yield responses were 16 NL, 19 linear (L), and 15 nonresponsive (mean, M). NL responsive trials were initially responsive to N application up to an optimum yield, after which the yield plateaued. For the 16 NL responsive trials, Y_0 ranged from 272 to 1259 kg ha⁻¹ with a mean $\pm$ standard error of 839 $\pm$ 85 kg ha⁻¹. For the 19 L responsive trials, Y_0 ranged from 451 to 1837 kg ha⁻¹, averaging 1168 $\pm$ 95 kg ha⁻¹. For the 15 M trials, Y_0 ranged from 709 to 1992 kg ha⁻¹, averaging 1293 $\pm$ 87 kg ha⁻¹.

The number of N responsive trials (i.e., sites with EONR > 0 kg ha⁻¹) varied among physiographic regions: 33% in the Flatwoods, 67% in the Coastal Plain, 50% in the Sandhills, and 0% in the Piedmont. Mean Y_0 was not different among physiographic regions: Flatwoods (1020 $\pm$ 142 kg ha⁻¹), Coastal Plain (1119 $\pm$ 75 kg ha⁻¹), Sandhills (1112 $\pm$ 225 kg ha⁻¹), and Piedmont (1112 $\pm$ 106 kg ha⁻¹). The history of conservation practices significantly affected Y_0 (Table 3), with a long-term history of cover crops (1308 $\pm$ 83 kg ha⁻¹) and PL (1155 $\pm$ 75 kg ha⁻¹) having higher Y_0 compared to sites with no conservation history (782 $\pm$ 84 kg ha⁻¹). Similarly, history of conservation

TABLE 2 Estimated parameters (Y_0 , A , and B , kg ha^{-1}) of nonlinear (Exponential, NL), linear (L), or mean (M) models fitted to lint yield response to N fertilizer application for each trial, including the model performance evaluated using the coefficient of determination (r^2). The control yield (Y_0 , kg ha^{-1}), maximum attainable yield (Y_{MAX} , kg ha^{-1}), relative yield (RY, %), economic optimum N rate (EONR, kg ha^{-1}); profit maximizing yield (PMY, kg ha^{-1}), and nitrogen factor (Nf, kg N kg^{-1} Lint) are also included for sites responsive to N application. Lint yield response and optimum N characteristics of all sites were categorized into physiographic regions of South Carolina.

Site	Model	Y_0	A	B	r^2	Y_{MAX}	RY	EONR	PMY	Nf
Flatwoods										
A	NL	883	299	0.03	0.51	1172	75	73	1135	0.06
N1	L	451	–	0.87	0.19	569	79	0	451	0.00
N2	NL	272	151	0.02	0.22	412	66	46	363	0.13
Q1	M	1518	–	–	–	1518	100	0	1518	0.00
Q2	M	967	–	–	–	967	100	0	967	0.00
R1	NL	1078	137	0.04	0.04	1214	89	38	1185	0.03
R2	M	1344	–	–	–	1344	100	0	1344	0.00
S1	L	1301	–	0.91	0.03	1423	91	0	1301	0.00
S2	M	1368	–	–	–	1368	100	0	1368	0.00
Coastal Plain										
B	L	773	–	1.78	0.11	1012	76	135	1012	0.13
C	NL	1128	78	0.02	0.14	1198	94	5	1134	0.00
D	NL	1189	389	0.02	0.19	1553	77	93	1519	0.06
E	L	1163	–	1.73	0.13	1395	83	135	1395	0.10
F	M	1992	–	–	–	1992	100	0	1992	0.00
J	L	1813	–	0.00	0.00	1813	100	0	1813	0.00
K	L	932	–	4.95	0.58	1599	58	135	1599	0.08
L	NL	275	64	0.01	0.06	329	84	0	275	0.00
M	NL	299	141	0.02	0.17	435	69	43	391	0.11
O1	NL	1237	621	0.01	0.49	1751	71	135	1751	0.08
O2	L	1320	–	2.21	0.08	1618	82	135	1618	0.08
OA	L	1011	–	2.71	0.10	1376	74	135	1376	0.10
OB	M	906	–	–	–	906	100	0	906	0.00
T1	L	1583	–	3.17	0.42	2010	79	135	2010	0.07
T2	L	1620	–	2.21	0.30	1918	85	135	1918	0.07
TA	M	1393	–	–	–	1393	100	0	1393	0.00
TB	M	1447	–	–	–	1447	100	0	1447	0.00
U1	L	526	–	5.31	0.67	1241	42	135	1241	0.11
U2	NL	819	251	0.03	0.25	1066	77	61	1031	0.06
UA	M	1014	–	–	–	1014	100	0	1014	0.00
UB	NL	947	188	0.04	0.23	1134	84	47	1104	0.04
V	NL	1002	1196	0.01	0.74	1860	54	135	1860	0.07
VA	L	1541	–	2.70	0.21	1904	81	135	1904	0.07
VB	M	1401	–	–	–	1401	100	0	1401	0.00
W1	NL	554	380	0.07	0.39	934	59	46	915	0.05
W2	L	828	–	2.34	0.18	1144	72	135	1144	0.12
X	NL	1019	230	0.03	0.11	1246	82	55	1214	0.05
XA	L	1136	–	0.67	0.04	1227	93	0	1136	0.00
XB	L	1455	–	0.07	0.00	1464	99	0	1455	0.00
Z	NL	1259	509	0.02	0.75	1732	73	108	1707	0.06

(Continues)

TABLE 2 (Continued)

Site	Model	Y_0	A	B	r^2	Y_{MAX}	RY	EONR	PMY	Nf
Sandhills										
G	M	709	–	–	–	709	100	0	709	0.00
H	M	1793	–	–	–	1793	100	0	1793	0.00
I	L	1837	–	0.91	0.02	1960	94	0	1837	0.00
P1	L	877	–	4.29	0.64	1455	60	135	1455	0.09
P2	NL	617	655	0.02	0.53	1185	52	135	1185	0.11
PA	NL	840	103	0.02	0.02	939	90	30	894	0.03
Piedmont										
YA	M	1202	–	–	–	1202	100	0	1202	0.00
YC1	M	1014	–	–	–	1014	100	0	1014	0.00
YC2	L	742	–	0.32	0.01	785	95	0	742	0.00
YK1	M	1323	–	–	–	1323	100	0	1323	0.00
YK2	L	1277	–	0.02	0.00	1280	100	0	1277	0.00

TABLE 3 Statistical significance (p -value) of cotton yield response parameters and pre-treatment residual soil nitrate-N (RSN; kg ha⁻¹) and ammonium-N (RSA; kg ha⁻¹) contents at 0- to 10-cm and 0- to 60-cm depths as influenced by management practices (tillage, previous crop, and water regime), physiographic region (Flatwood, Coastal Plain, Sandhills, and Piedmont), and history of conservation (cover crops, poultry litter, and no conservation practices) across South Carolina (2021–2023) based on Kruskal–Wallis test.

Factor	Y_0	Y_{MAX}	RY	EONR	PMY	Nf	RSN _{0–10 cm}	RSA _{0–10 cm}	RSN _{0–60 cm}	RSA _{0–60 cm}
Tillage	0.82	0.30	0.09	0.04	0.27	0.04	0.15	0.36	0.35	0.95
Previous crop	0.25	0.19	0.66	0.94	0.22	0.89	0.32	0.98	0.07	0.29
Water regime	0.05	0.03	0.71	0.09	0.02	0.30	0.29	0.16	0.64	0.19
Physiographic region	0.94	0.28	0.06	0.02	0.26	0.06	0.16	0.74	0.36	0.02
History of conservation practices	0.01	0.06	0.01	0.18	0.08	0.08	0.004	0.03	0.02	0.12

Note: Significant effects ($p < 0.1$) are highlighted in bold. Y_0 : Control yield (no nitrogen application); Y_{MAX} : Maximum attainable yield; RY: Relative yield (%); EONR: Economic optimum nitrogen rate (kg ha⁻¹); PMY: Profit maximizing yield; Nf: Nitrogen factor (kg N kg⁻¹ lint).

practices also affected Y_{MAX} and PMY, with higher values under a long-term history of cover crops practices (Y_{MAX} : 1515 ± 79 kg ha⁻¹ and PMY: 1498 ± 82 kg ha⁻¹) compared to NCPs (Y_{MAX} : 1109 ± 121 kg ha⁻¹ and PMY: 1089 ± 123 kg ha⁻¹). Water regime also affected Y_0 , Y_{MAX} , and PMY, with higher values for sites with irrigated (Y_0 : 1281 ± 99 kg ha⁻¹, Y_{MAX} : 1506 ± 95 kg ha⁻¹, and PMY: 1490 ± 94 kg ha⁻¹) compared to dryland (Y_0 : 1022 ± 67 kg ha⁻¹, Y_{MAX} : 1204 ± 68 kg ha⁻¹, and PMY: 1182 ± 71 kg ha⁻¹).

3.3 | Cotton N response and soil N status across management practices

The EONR varied widely across sites, ranging from 0 to 135 kg ha⁻¹, that is, both the technical minimum and maximum levels possible in this experimental design. Physiographic region had a significant effect ($p = 0.02$) on EONR

and Nf ($p = 0.06$), with higher EONR and Nf at Coastal Plains (EONR: 69 kg ha⁻¹, Nf: 0.05 kg kg⁻¹) compared to Piedmont (EONR: 0 kg ha⁻¹, Nf: 0.00 kg kg⁻¹), while Flatwoods (EONR: 17 kg ha⁻¹, Nf: 0.02 kg kg⁻¹) and Sandhills (EONR: 50 kg ha⁻¹, Nf: 0.04 kg kg⁻¹) were not significantly different than any of the regions. The interquartile range of EONR was 0–135 kg ha⁻¹ in the Coastal Plain, 0–135 kg ha⁻¹ in the Sandhills, 0–42 kg ha⁻¹ in the Flatwoods, and 0–0 kg ha⁻¹ in the Piedmont.

The history of conservation practices significantly affected Nf (Table 3), with highest values for NCPs (0.07 kg N kg⁻¹ yield), while lowest values were for sites under long-term use of cover crops (0.03 kg kg⁻¹) and PL (0.02 kg kg⁻¹). The history of conservation practices substantially enhanced residual soil N, with PL applications showing ~2.5-fold higher RSN at 0- to 10-cm and 0- to 60-cm depths (32.9 ± 3.8 kg ha⁻¹ and 73.5 ± 10.6 kg ha⁻¹, respectively) compared to sites with NCPs (12.2 ± 2.6 and 29.2 ± 6.4 kg ha⁻¹, respectively).

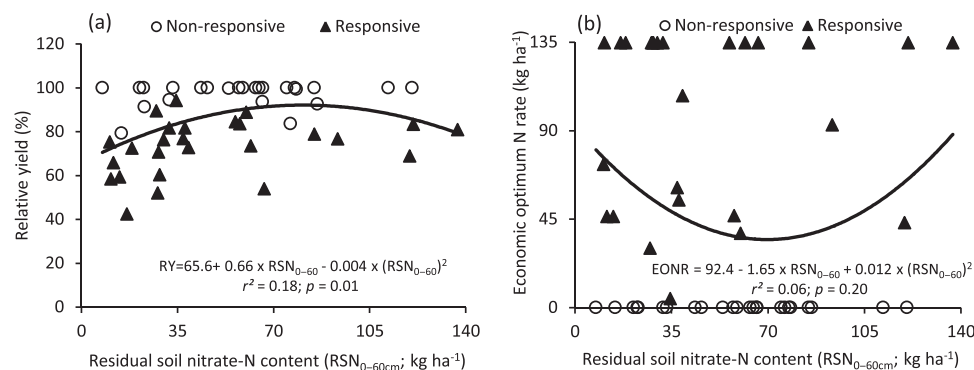


FIGURE 2 Quadratic relationship between relative yield (%) and pre-treatment residual soil nitrate-N content (RSN; kg ha⁻¹) at 0- to 60-cm depth (a) and quadratic relationship between economic optimum N rate (EONR; kg ha⁻¹) and RSN content at 0- to 60-cm depth (b). Non-responsive sites (circles) and responsive sites (triangles) are distinguished.

Similarly, RSA at 0–10 cm was nearly doubled under PL (11.7 ± 2.0 kg ha⁻¹) and CC-L (11.8 ± 1.8 kg ha⁻¹) compared to NCPs (5.9 ± 0.6 kg ha⁻¹). No-tillage sites had lower EONR (14 kg ha⁻¹) and Nf (0.01 kg kg⁻¹) compared to strip tillage (EONR: 59 kg ha⁻¹, Nf: 0.04 kg kg⁻¹). Sites with irrigation (73 kg ha⁻¹) had higher EONR compared to dryland sites (41 kg ha⁻¹).

RY ranged from 42% to 100%, with a mean value of 85%. Physiographic regions had a significant effect on RY, with highest at the Piedmont region (99%) compared to the Coastal Plain (82%). Physiographic region also affected RSA content at 0- to 60-cm depth ($p = 0.02$) with significantly higher values at Flatwood (67.4 ± 7.1 kg ha⁻¹) compared to Coastal Plain (52.0 ± 6.7 kg ha⁻¹), Piedmont (44.5 ± 4.0 kg ha⁻¹), and Sandhills (39.2 ± 3.1 kg ha⁻¹). Previous crop influenced RSN content at 0- to 60-cm depth ($p = 0.07$), with legumes (62.9 ± 8.6 kg ha⁻¹) and corn (60.7 ± 10.5 kg ha⁻¹) maintaining higher levels than cotton (41.5 ± 5.8 kg ha⁻¹). Among all the management factors, tillage and history of conservation practices had a significant effect on RY (Table 3), and history of PL application (95%) and CC-L use (87%) had higher RY compared to NCPs (72%). Similarly, sites with no-tillage had a higher RY (94%) compared to strip-tillage (83%).

RY showed a positive quadratic relationship with RSN content at 0- to 60-cm depth ($r^2 = 0.18$; $p = 0.01$; Figure 2a). However, EONR did not have a significant relationship with RSN or with RSA content at depths of 0–60 cm (Figure 2b) or 0–10 cm. The relatively low r^2 values indicate weak predictive relationships between pre-treatment soil N and cotton N response parameters.

4 | DISCUSSION

The objective of this study was to identify the factors influencing cotton lint yield response functions to N fertilizer application across a diversity of sites in South Carolina,

which included variations delineated by physiographic region and management practices. Cotton lint yield was responsive (EONR > 0 kg ha⁻¹) at 52% (26 of 50) of the trials, exhibiting wide variation in the apparent need for N fertilizer input. Our results are consistent with the findings of Main et al. (2013), in which cotton yield was responsive at 55% (11 of 20) of trials across cotton-producing states in the United States. Variability in lint yield responsiveness to N application has been attributed to different geographic locations, weather, and management practices, all of which could affect soil N availability (Li et al., 2019, 2020; Pettigrew & Zeng, 2014).

The variation in cotton yield responses, ranging from non-linear to linear to mean, within each physiographic region suggests a major challenge for optimizing cotton N fertilizer recommendations. EONR varied widely, ranging from 5 to 135 kg ha⁻¹ at the responsive sites, with physiographic region significantly affecting EONR ($p = 0.02$). The extent of responsiveness and EONR was maximum at Coastal Plain and Sandhills, while the minimum was observed at the Piedmont region. The prevalence of responsive trials and greater mean EONR in the Coastal Plain and Sandhills (50 – 69 kg ha⁻¹) compared with the Piedmont (0 kg ha⁻¹) could relate to contrasting soil properties and climatic conditions. Coarse-textured, well-drained soils in coastal regions, combined with high precipitation, contributed to nitrate leaching and a low nutrient holding capacity, thus decreasing N availability for plant uptake at lower rates (Hubbard et al., 2004; Pokhrel et al., 2024; Raza & Farmaha, 2022; Wiatrak & Liu, 2014). In contrast, the Flatwoods, despite similar precipitation and temperature patterns as the Coastal Plain, showed more non-responsive sites with a mean EONR of 17 kg ha⁻¹, likely due to higher soil organic matter content and enhanced N mineralization rates in these poorly drained soils (Quemada & Cabrera, 1995; Sahrawat, 2010; Watts et al., 2001). The Piedmont region exhibited the fewest responsive sites and lowest mean EONR of 0 kg ha⁻¹, attributable to fine-textured, clay-rich soils with high nutrient retention capacity (Markewich

et al., 1990; Tahir & Marschner, 2017) and a higher prevalence of sites with long-term PL application that increased soil N availability (Adeli et al., 2011; Sanchez & Mylavarapu, 2011).

The positive quadratic relationship between RY and RSN content at 0–60 cm (Figure 2a) demonstrates that soil N availability can partially offset the need for additional fertilizer N inputs (Main et al., 2013; Pabuayon et al., 2021). However, the relatively low r^2 value (18%) suggests that RSN and RSA alone cannot reliably predict N fertilizer requirements. This limitation can be attributed to the instability of residual soil N, which is highly susceptible to leaching losses, particularly in the sandy-textured soils typical of the Coastal Plain region (Hubbard et al., 2004; Pisani et al., 2017). These findings emphasize the need for determining soil N supplying capacity using multiple N fractions to better explain the variability in cotton N response.

The history of conservation management practices emerged as the most influential management factor, significantly affecting Y_0 , Y_{MAX} , RY, PMY, and the Nf. Sites with CC-L and PL application showed the highest Y_0 and RY, consistent with previous studies demonstrating the benefits of conservation practices over conventional management (Adeli et al., 2011; Boquet et al., 2004; Mitchell & Tu, 2005; Nouri et al., 2019; Toler et al., 2019). The contribution of conservation practices toward improving soil N availability was evident in our residual soil N measurements, with PL applications showing ~2.5-fold higher RSN compared to sites with NCPs. The Nf, representing the quantity of N needed per unit of lint produced, was lowest for sites with conservation practices, highlighting their role in improving the N availability and reducing reliance on external N inputs. These effects can be attributed to soil N accumulation in both organic and inorganic forms, with biologically active organic matter serving as an important N source (Franzluebbers, 2018; 2020). The long-term positive impacts of conservation practices on soil fertility align with the findings from Ahmad et al. (2022) and Nyakatawa et al. (2001), which reported improved soil organic matter and nutrient retention in cotton fields under conservation management.

Interestingly, other management factors, such as current tillage practice, previous crops, and water regime, had variable effects on cotton lint yield response parameters. These results align with previous studies that have reported a significant or no effect of these factors on lint yield (Balkcom et al., 2006; Boquet et al., 2004; Bronson et al., 2001). Even though tillage practices in this study were limited to conservation methods (no-till and strip-till), reducing the contrast needed to observe significant differences in cotton yield, it had a significant effect on RY, EONR, and Nf. Water regime had a significant effect on Y_0 , Y_{MAX} , EONR, and PMY and while having no effect on RY and Nf. These results align with previous studies observing higher cotton yield with supplemental

irrigation compared to nonirrigated cotton (Balkcom et al., 2006; Sui et al., 2014), while higher EONR was observed for irrigated sites. The N requirements for irrigated cotton can be higher because of water availability supporting cotton growth, yield potential, and N uptake, though it can also increase N losses via leaching (Kumar et al., 2022; Liao et al., 2024; Rong & Xuefeng, 2011). Additionally, adequate growing-season precipitation may have minimized the contrast between dry-land and irrigated water regimes. The absence of clear effects from current management practices might also be attributed to the overriding influence of N fertilization and the complex interaction between these management factors.

Results from this study have important implications for N management in cotton production across the southeastern United States. The wide range of EONRs highlights the limitations of a uniform N recommendation and the potential for under- and over-application of N. The current N fertilizer recommendation in South Carolina of 78–112 kg ha⁻¹ (Jones et al., 2023) substantially exceeds EONR at 68% of the sites and the mean EONR values observed in each physiographic region (Flatwoods: 17 kg ha⁻¹; Coastal Plain: 69 kg ha⁻¹; Sandhills: 50 kg ha⁻¹; and Piedmont: 0 kg ha⁻¹). This discrepancy highlights the potential for significant over-application of N when following current blanket recommendations. A potential contributing factor to why we observed lower N requirements than currently recommended could be enhanced nutrient uptake efficiency and internal N use by modern cotton varieties (Pabuayon et al., 2021). Modern cultivars utilize nutrients 27% more effectively than older varieties (Singh et al., 2024), showing improved use efficiency of N (20%), phosphorus (23%), and potassium (24%) by breeding for lint yield (Rochester & Constable, 2015). Our results suggest that current N recommendations may need refinement to reflect greater N use efficiency of modern cotton varieties.

The strong effect of conservation history on yield response parameters suggests that long-term soil and crop management should be considered when developing N fertilizer recommendations. An integrated set of soil properties that expresses the effects of conservation management on soil N availability would be ideal to help characterize the many interactive management factors and duration of implementation. Biologically active soil carbon and N were shown to be partially effective in corn production systems (Franzluebbers, 2020). Producers with a history of conservation practices may be able to reduce N inputs without sacrificing yield. However, the complexity of factors influencing cotton response to N fertilization emphasizes the need for integrating multiple information sources, including soil tests, crop monitoring, historical yield, and weather data, to fine-tune N management at the field level. Future research should focus on developing decision support tools that incorporate these factors to provide more precise, site-specific N recommendations for cotton production in the region.

5 | CONCLUSIONS

This extensive study of cotton lint yield response to N fertilization across diverse environments in South Carolina yielded several important insights with significant implications for sustainable cotton production. Cotton lint yield was responsive to N fertilizer application in 52% of trials, while EONR was $<78 \text{ kg ha}^{-1}$ in 68% of trials. These trials demonstrated substantial variability in cotton lint yield response to N fertilization across physiographic regions and history of conservation use, underscoring the limitations of uniform N recommendations and highlighting the need for site-specific recommendations tailored to local environmental and management conditions.

The wide interquartile range of EONR observed among sites ($0\text{--}135 \text{ kg ha}^{-1}$) emphasized the potential for under- and over-application of N when using blanket recommendations. Our hypothesis that sites with long-term conservation practices would have lower N requirements was supported by significantly lower Nf at sites with long-term history of cover cropping and PL application compared to NCPs. The significant effects of conservation history on yield without N fertilizer (Y_0) and RY further demonstrated the long-term benefits of sustainable soil management practices.

The lack of significant effects from current-year previous crop, tillage, and water regime on different yield response parameters, contrary to some previous studies, suggests that the long-term history of conservation practices and physiographic characteristics may override the influence of these short-term factors. However, irrigation increased cotton yield, and no-tillage reduced EONR. This research highlights the need for region-specific N recommendations based on the long-term history of conservation and current management practices. Conservation management reduced cotton N requirements and provided more consistent, predictable responses for sustainable cotton production in the southeastern United States.

AUTHOR CONTRIBUTIONS

Shikha Dubey: Formal analysis; investigation; methodology; project administration; software; visualization; writing—original draft; writing—review and editing. **Bhupinder S. Farmaha:** Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; software; supervision; validation; visualization; writing—review & editing. **Alan J. Franzluebbbers:** Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; supervision; validation; visualization; writing—review and editing. **William C. Bridges:** Data curation; formal analysis; methodology; supervision; validation; writing—review and editing. **Michael A. Jones:**

Methodology; supervision; validation; writing—review and editing. **Gaylon D. Morgan:** Conceptualization; funding acquisition; methodology; project administration; resources; supervision; validation; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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