Satellite-based on-farm variable rate nitrogen management and main spatial drivers of cotton yield, profitability, and nitrogen use efficiency

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Abstract.

Georgia is the second largest cotton (Gossypium hirsutum L.) producing state in the USA. Nitrogen (N) fertilizer is one of the main inputs required to optimize cotton lint yield and quality, while also being a large input cost. Spatial variability of soil properties and management practices can create zones within a field with different yield and N loss potentials. Such conditions can potentially benefit from variable rate N (VRN) management, yet studies on this are lacking. The objectives of this study were to i) contrast fixed and VRN management and their impact on cotton lint yield, profitability, and *N use efficiency; and ii) dissect the main drivers of cotton lin*t yield, profitability, and *N use efficiency. For that, an irrigated on-farm study was conducted in 2023 near Sylvania, Georgia. The 25-ha field was characterized using a Veris MSP3 collecting apparent soil electrical conductivity (EC) and elevation. The experimental design was a randomized complete block with six replicates. The treatment design comprised different N rates applied in-season including 0, 22, 45, 67 (grower standard practice) and 90 kg N ha^{-1} applied as fixed-rate plus a VRN treatment. The VRN treatment was determined based on Sentinel-2 imagery. The field was harvested with a yield monitor-equipped cotton picker. Soil EC, relative elevation, as-applied N, and cleaned yield data were co-located to a same grid. For each grid cell, partial profit and N use efficiency were then calculated.* Data was analyzed at two spatial scales: strip- and cell-level. Strip-level yield, partial profit, and PFP_N were analyzed as a function of plot nested in block (random) and side-dress N treatment (fixed). Cell-level yield, partial profit, and PFP_N were analyzed using a conditional inference tree algorithm as a function of soil shallow and deep EC, relative elevation, and in-season as-applied N rate. In-season VRN treatment rates ranged from 5 to 20 kg N ha^{-1}. Strip-level mean lint yield ranged from 1,003 to 1,185 kg ha^{-1}, with highest yields observed when 67 and 90 kg N ha^{-1} were applied at side-dress. Strip-level mean profit ranged from 1,879 to 2,068 \$ ha^{-1}, with highest profits observed under 22, 67, 90 kg N ha^{-1} and VRN treatments. Strip-level mean PFP_N ranged from 6 to 10 kg lint kg^{-1} N with highest efficiency observed only under the VRN treatment. The main controllers of spatial variability of yield, partial profit, and PFP_N were similar but ranked differently. For yield, greater in-season N rates coupled with greater soil shallow EC and lower elevation created the most optimum conditions. For profit, soil EC and relative elevation were the main drivers, with in-season N rate playing a minor role. For PFP_N, in-season N rate was the most dominant driver, with low N rates creating the largest efficiencies. These results point to the complexity of managing N on commercial field scales and the difficulty of identifying conditions that can optimize different metrics. Future studies are important to better elucidate the potential of VRN in Georgia and its impact on growers and the environment.

Keywords.
Fertilizer, lint, satellite, remote sensing, strip trial, variable rate technology.

Introduction

In the United States of America, Georgia is the second largest cotton (*Gossypium hirsutum* L.) producing state, responsible for 2.6 million bales produced in 2022 (USDA-NASS, 2024). In Georgia, cotton is the most economically important row crop, with ~514,000 ha harvested (USDA-NASS, 2024) and $USD 1.5 billion in economic impact in the state economy in 2022 (The University of Georgia, 2022).

Nitrogen (N) fertilizer is one of the main inputs required to optimize cotton lint yield and quality, while also being a large input cost representing ~25% of variable costs (University of Georgia, 2023). As a non N-fixing crop, applying sub-optimum N rates in cotton can curtail yield and quality whereas applying over-optimum N rates can increase production costs without a return, lower nutrient use efficiency, and increase N environmental losses (Pisani et al., 2017; Scheer et al., 2023). In the specific case of cotton, the optimum N rate window is narrower than in other crops like corn. That is because even small rates of N applied beyond the optimum level promote excessive vegetative growth in lieu of reproductive and thereby reduce lint yield and quality (Pokhrel et al., 2023).

Spatial variability of soil properties and management practices can create zones within a field with different yield and N loss potentials (Boydell & McBratney, 2002), especially in the coarse-textured, irrigated, and hot and humid conditions in which cotton is commonly grown in Georgia. Such conditions can potentially benefit from variable rate N management, yet studies on this are lacking especially conducted on-farm. Therefore, the objectives of this on-farm study were to i) contrast fixed and variable rate N management and their impact on cotton lint yield, profitability, and N use efficiency; and ii) dissect the main spatially variable drivers of cotton lint yield, profitability, and N use efficiency.

Materials and Methods

An irrigated on-farm study was conducted in 2023 near Sylvania, Georgia in collaboration with a cotton grower. The soil of the field is classified as a Dothan-Norfolk complex (Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture, 2024). The 25-ha field was characterized using a Veris MSP3 equipment collecting apparent soil electrical conductivity (EC) at two depths (shallow and deep) and elevation. The grower conventional N management was comprised of planting an eight-species mixture of cover crop in the previous fall, followed by the application of 1.8 Mg ha^{-1} of chicken litter in the following spring, and in-season top-dressing of 67 kg N ha^{-1} between first square and first bloom. Chicken litter was broadcast to the entire field on March 4, and cover crops were terminated on May 1. Cotton variety Phytogen 545 was planted on May 12.

The experimental design was a randomized complete block with six replicates. The treatment design comprised different levels of N applied in-season including 0, 22, 45, 67 (grower standard practice) and 90 kg N ha^{-1} applied as fixed-rate plus a variable rate N (VRN) treatment (Figure 1).

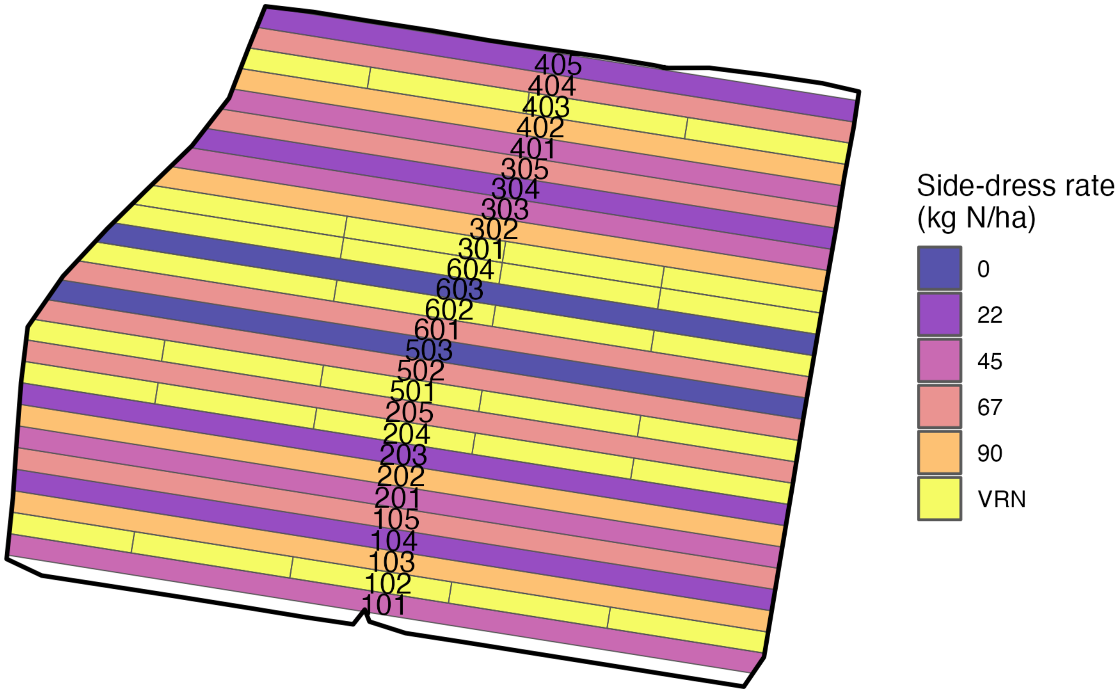

Figure 1. Layout of the field study. East-west strips received one of the seven nitrogen (N) rate treatments. The variable rate nitrogen (VRN) strips were further segmented into different splits, each receiving a different N rate based on satellite data.

The VRN treatment was determined based on Sentinel-2 imagery (3-5 days temporal resolution, 10-m spatial resolution) from the week preceding the in-season application time. Imagery in the form of green normalized difference vegetation index (GNDVI) was utilized to generate the VRN recommendation (Figure 2a). First, GNDVI pixel values were extracted (Figure 2b) and then averaged (Figure 2c) within each of the VRN segments (123 m long x 17 m wide) within a VRN treatment strip. Then, a block-specific N-sufficient reference GNDVI value was determined using the virtual reference concept [i.e., 95^{th} quantile of the block GNDVI distribution, Figure 2d-e; Holland and Schepers (2013)]. VRN segment mean GNDVI values were divided by the block-specific reference values to generate a sufficiency index. Finally, the sufficiency index value, grower-decided optimum N rate (i.e., 120 kg N ha^{-1}), and N credits from cover crop and chicken litter (i.e., 96 kg N ha^{-1}) were used with the Holland-Schepers algorithm (Holland and Schepers, 2010) to determine a VRN to be applied to each segment within the VRN strips (Figure 2f). All in-season N treatments, including VRN, were applied utilizing a variable rate buggy disc spreader in the form of Environmentally Smart N (ESN), a coated urea fertilizer (44% N), on July 12.

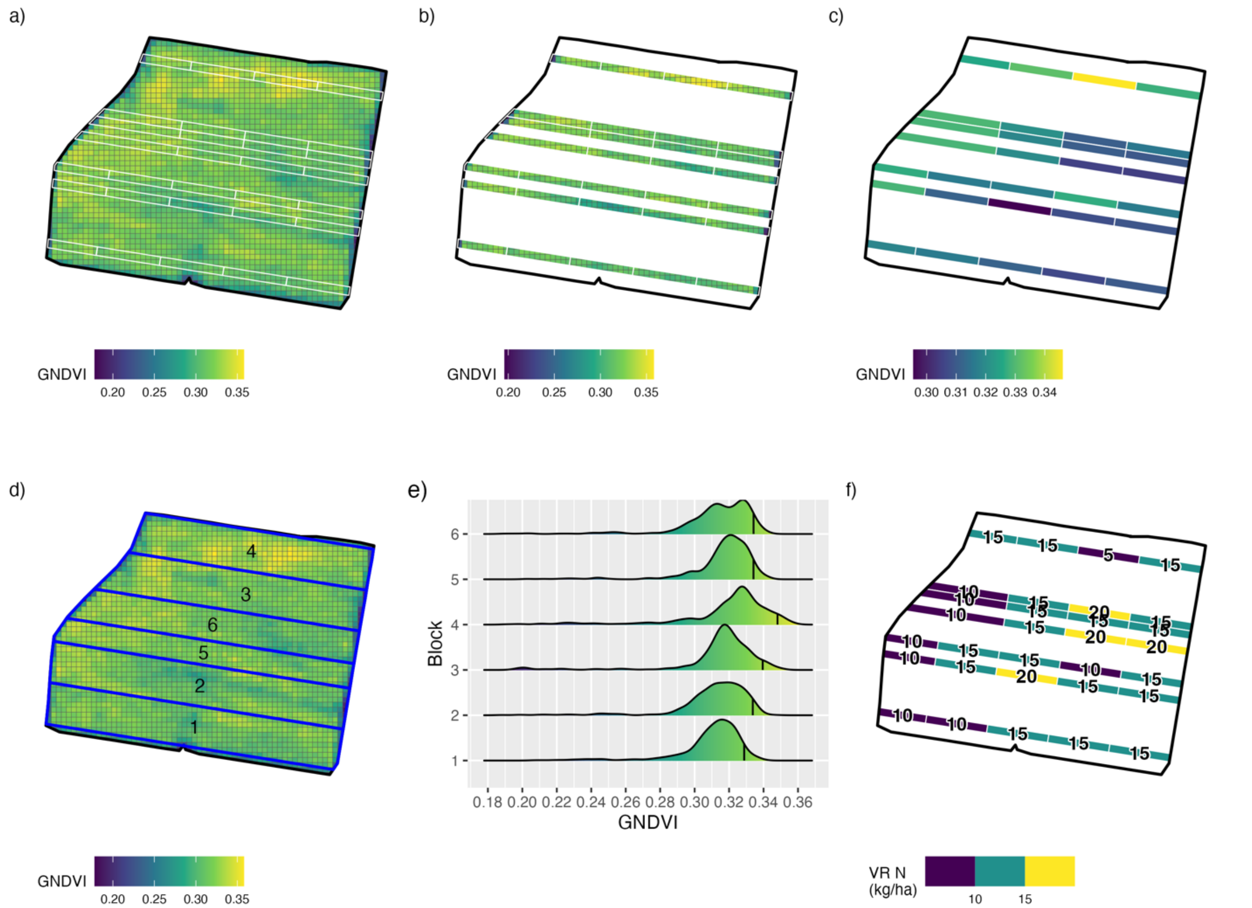

Figure 2. Steps followed to create a satellite sensor-based variable rate nitrogen (VRN) prescription. Sentinel-2 imagery was retrieved from the week prior to VRN for the entire field and used to calculate the green normalized difference vegetation index (GNDVI) (a); pixels were extracted only for the VRN east-west long strips (b); within the VRN strips, GNDVI pixels were averaged for each segment (c); all pixels within each statistical block (d) were utilized to calculate a virtual reference value as the 95th quantile of all block-specific GNDVI pixel value distribution (e, vertical lines within statistical distribution represent the 95th quantile); and final VRN prescription based on values from c) and e) applied to the Holland-Schepers algorithm and assuming optimum N rate and credits described in the text, where numbers in the plot represent prescribed rate, in kg ha^{-1} (f).

The field was harvested with a yield monitor-equipped cotton picker on November 4. Soil EC, relative elevation (calculated as elevation of a pixel divided by the median elevation of the field), as-applied N, and cleaned yield data were co-located to a same grid with a cell size of 3 x 17 m (Figure 3). For each grid cell, partial profit and N use efficiency were then calculated. Partial profit was calculated based on a cotton lint price of \$1.89 kg^{-1} lint (\$0.85 lb^{-1}) and an in-season N cost of \$0.67 kg^{-1} (\$0.3 lb^{-1}). N use efficiency was calculated as partial factor productivity of N (PFP_N) by dividing lint yield by the total applied N rate (pre-plant + in-season as-applied).

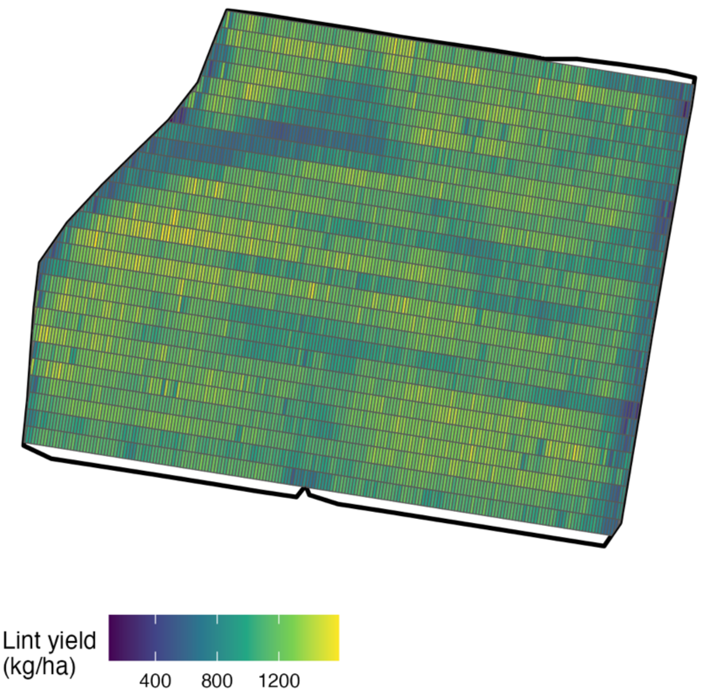

Figure 3. Depiction of cleaned yield monitor data, in kg lint ha^{-1}, averaged to a grid with cell size of 3 x 17 m.

Data was analyzed at two spatial scales: strip- and cell-level. Strip-level yield, partial profit, and PFP_N were analyzed in a mixed-effect analysis of variance model as a function of plot nested in block (random effects) and side-dress N treatment (fixed effect). Treatment means were compared using Fisher's LSD at an alpha level of 0.05. Cell-level yield, partial profit, and PFP_N were analyzed using a conditional inference tree algorithm as a function of soil shallow and deep EC, relative elevation, and in-season as-applied N rate.

Results and Discussion

In-season VRN treatment rates across all segments ranged from 5 to 20 kg N ha^{-1}, significantly lower than the grower conventional rate of 67 kg N ha^{-1}. Other studies evaluation VRN in cotton reported similar reductions in rate, ranging from 10% to 42% reductions compared to grower conventional rates (Stamatiadis et al., 2020; Yu et al., 2019). Strip-level mean lint yield ranged from 1,003 to 1,185 kg ha^{-1}, with highest yields observed when 67 and 90 kg N ha^{-1} were applied at side-dress (Figure 4). When pre-plant N application rates are considered, the total N rate (pre-plant + side-dress) that optimized yield added up to 163 and 186 kg N ha^{-1}. These results are similar to those reported by Pokhrel et al. (2023), who found 89 to 179 kg N ha^{-1} optimized cotton lint yield in similar field conditions in Georgia.

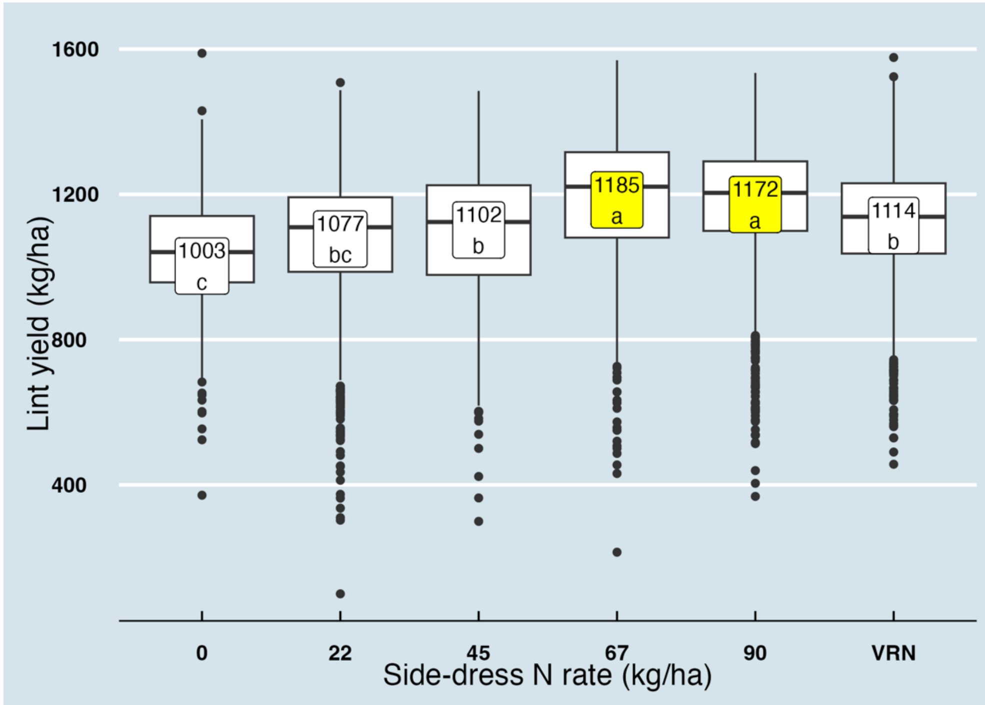

Figure 4. Boxplots of lint yield, in kg ha^{-1}, as a function of different side-dress nitrogen (N) rates, including a sensor-based variable rate N treatment (VRN). Boxplots sharing the same letter are not significantly different at alpha = 0.05.

Strip-level mean profit ranged from 1,879 to 2,068 $ ha^{-1}, with highest profits observed under 22, 67, 90 kg N ha^{-1} and VRN treatments (Figure 5). While VRN did not improve profitability in our study, others have reported increased profitability from VRN compared to fixed-rate management ranging from 72 to 270 $USD ha^{-1} on average, although some sites and years had a negative partial profit balance (Stamatiadis et al., 2020; Stefanini et al., 2019).

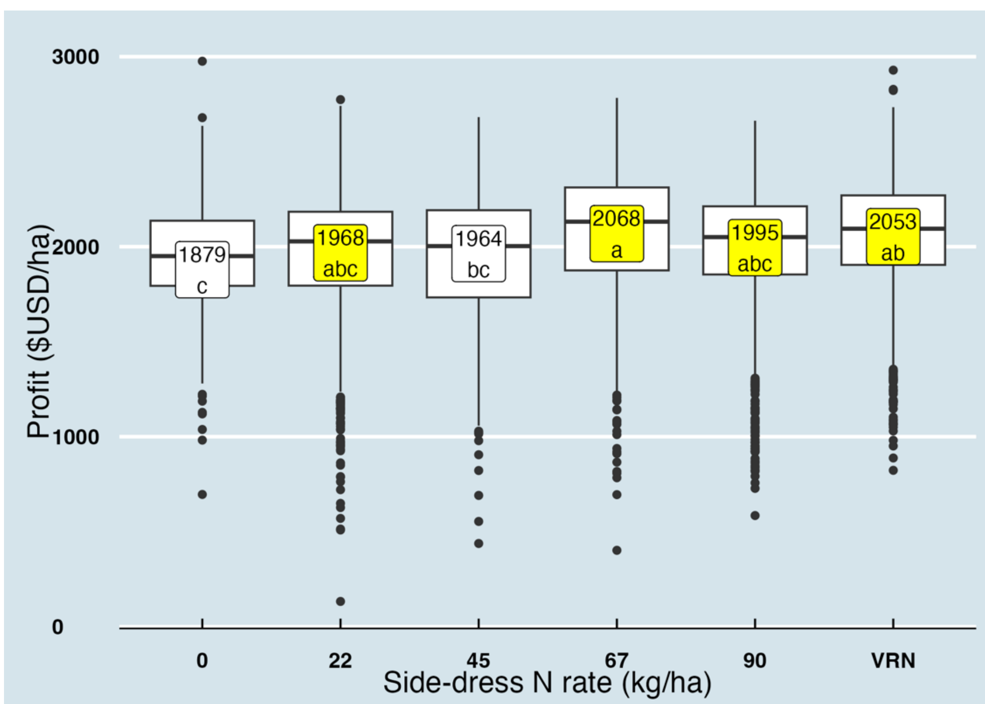

Figure 5. Boxplots of partial profit, in $USD ha^{-1}, as a function of different side-dress nitrogen (N) rates, including a sensor-based variable rate N treatment (VRN). Boxplots sharing the same letter are not significantly different at alpha = 0.05.

Strip-level mean PFP_N ranged from 6 to 10 kg lint kg^{-1} N with highest efficiency observed only under the VRN treatment (Figure 6). Similarly, other studies have found that VRN improved N use efficiency in 8-22% compared to fixed-rate management (Stamatiadis et al., 2020; Yu et al., 2019). Others have found no impact of VRN on N use efficiency (Stefanini et al., 2019).

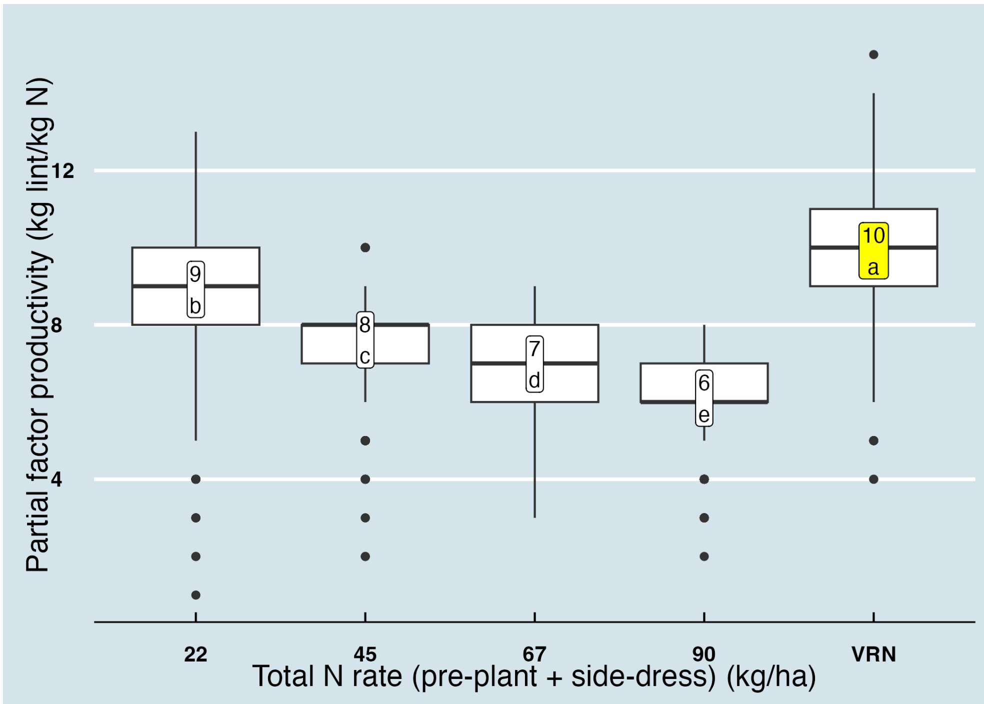

Figure 6. Boxplots of partial factor productivity of nitrogen (N), in kg lint kg N^{-1}, as a function of different side-dress N rates, including a sensor-based variable rate N treatment (VRN). Boxplots sharing the same letter are not significantly different at alpha = 0.05.

The most important variables affecting cell-level lint yield were, in decreasing order of importance, in-season as-applied N rate, relative elevation and soil shallow EC (Figure 7). Cell-level lint yield was optimized when as-applied in-season N rate was greater than 63 kg N ha^{-1}, soil shallow EC was > 19, and relative elevation was 0.99 (1284 kg lint ha^{-1}). The lowest yield levels were observed when as-applied in-season N was lower than 63 kg N ha^{-1}, and relative elevation was greater than the field median (580 to 983 kg lint ha^{-1}).

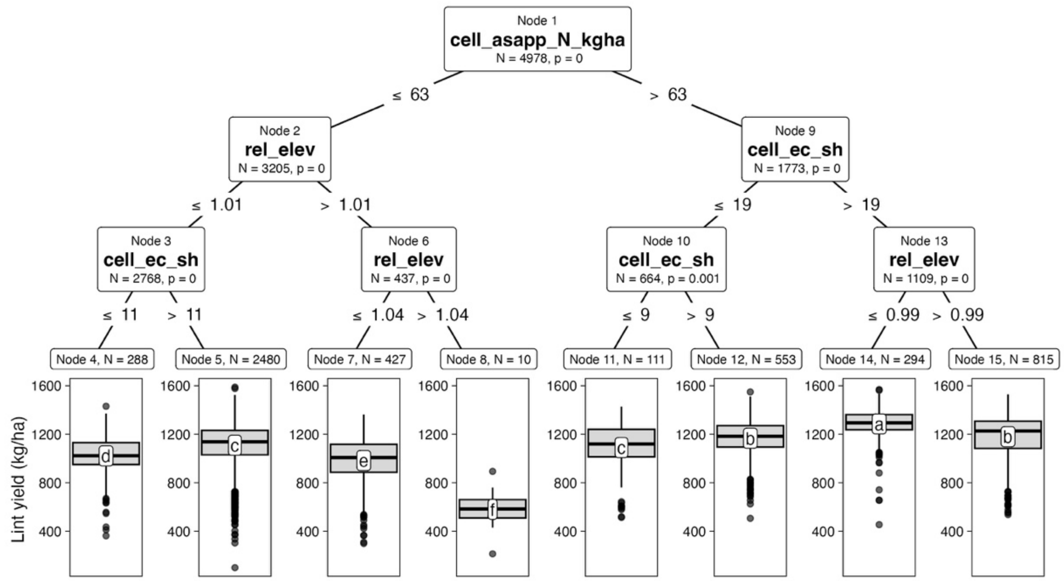

Figure 7. Conditional inference tree model of cotton lint yield, in kg ha^{-1}, explained by in-season as-applied nitrogen (N) fertilizer rate (cell_asapp_N_kgha), relative elevation (rel_elev), and shallow soil electrical conductivity (cell_ec_sh, in mS m^{-1}). Terminal node boxplots followed by the same letter are not significantly different at alpha = 0.05.

The most important variables affecting cell-level partial profit were, in decreasing order of importance, soil shallow EC, relative elevation, in-season as-applied N rate, and soil deep EC (Figure 8). Cell-level partial profit was optimized when soil shallow EC was greater than 13 mS m^{-1}, relative elevation was lower than the field median, and soil deep EC was greater than 1.3 mS m^{-1} (2,111 $ ha^{-1}). The lowest partial profit levels were observed when soil shallow EC was greater than 13 mS m^{-1} and relative elevation was 4% or greater than the field median (1,403 $ ha^{-1}).

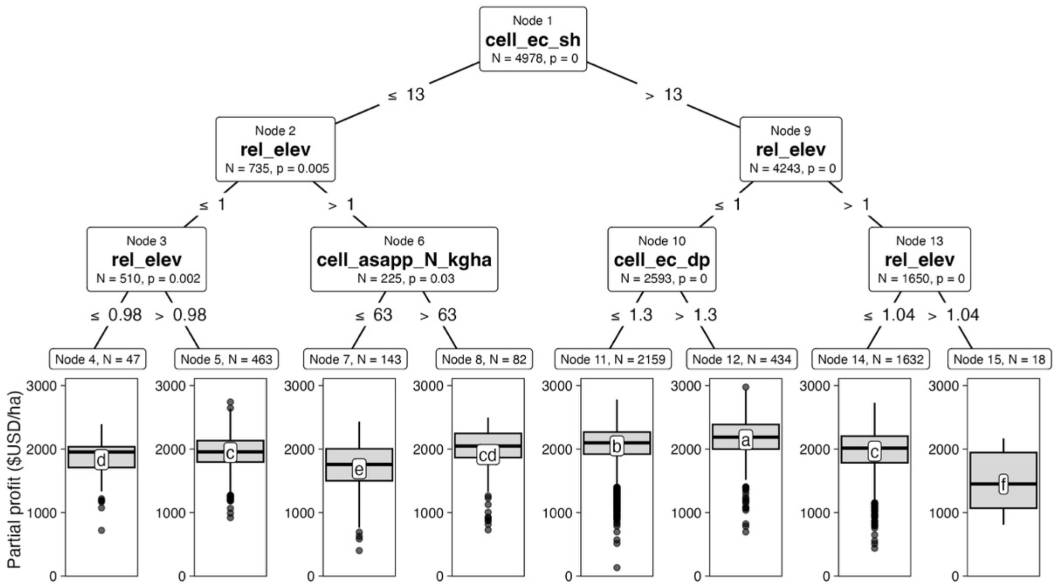

Figure 8. Conditional inference tree model of partial profit, in $USD ha^{-1}, explained by shallow soil electrical conductivity (cell_ec_sh, in mS m^{-1}), relative elevation (rel_elev), in-season as-applied nitrogen (N) fertilizer rate (cell_asapp_N_kgha), and deep soil electrical conductivity (cell_ec_dp, in mS m^{-1}). Terminal node boxplots followed by the same letter are not significantly different at alpha = 0.05.

The most important variables affecting cell-level PFP_N were, in decreasing order of importance, in-season as-applied N rate, soil shallow EC, and relative elevation (Figure 9). Cell-level PFP_N was optimized when as-applied in-season N rate was lower than 14 kg N ha^{-1} (10.6 kg lint kg^{-1} N). The lowest PFP_N levels were observed when as-applied in-season N rate was greater than 81 kg N ha^{-1} and relative elevation was 3% or greater than the field median (5.3 kg lint kg^{-1} N).

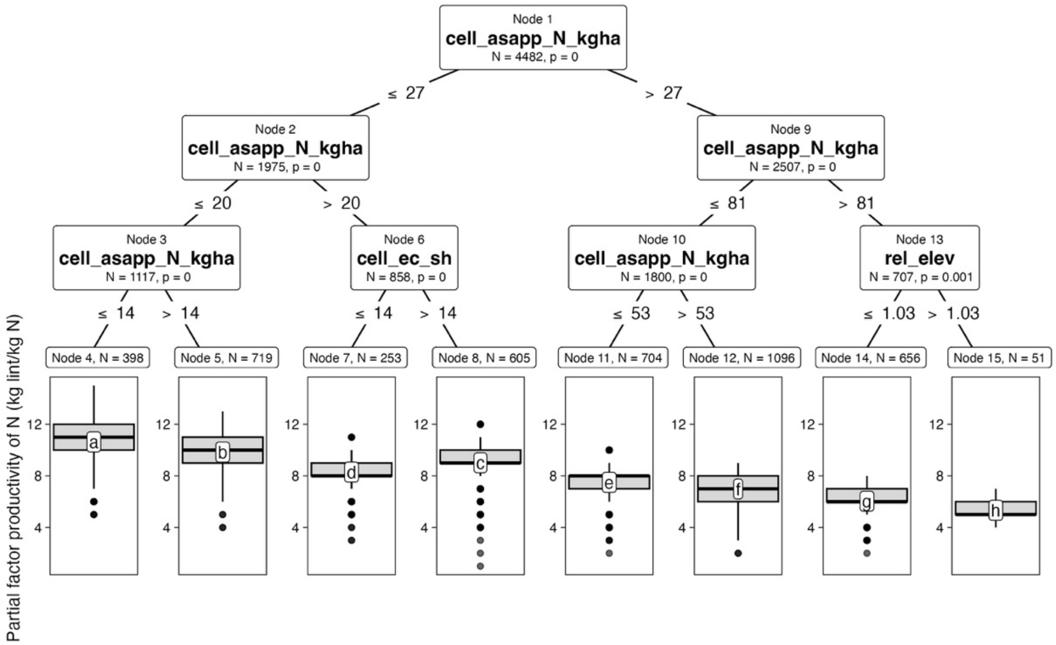

Figure 9. Conditional inference tree model of partial factor productivity of nitrogen (N), in kg lint kg^{-1} N, explained by in-season as-applied nitrogen (N) fertilizer rate (cell_asapp_N_kgha), shallow soil electrical conductivity (cell_ec_sh, in mS m^{-1}), and relative elevation (rel_elev). Terminal node boxplots followed by the same letter are not significantly different at alpha = 0.05.

While only higher in-season N rates were able to optimize lint yield, different in-season N rates were able to optimize partial profit, and only sensor-based was able to optimize PFP_N. Therefore, VRN was the only N management strategy that benefited both the grower by optimizing profit and the environment since greater N use efficiencies may reflect in lower N potential losses to the environment.

The main controllers of spatial variability of yield, partial profit, and PFP_N were similar, but their ranking of importance changed. For yield, greater in-season N rates coupled with greater soil shallow EC and lower elevation created the most optimum conditions. For profit, soil EC and relative elevation were the main drivers, with in-season N rate playing a minor role. For PFP_N, in-season N rate was the most dominant driver, with low N rates creating the largest efficiencies almost independently of soil or terrain features. These results point to the complexity of managing N on commercial field scales and the difficulty of identifying management practices and field conditions that can optimize different metrics related to production, profitability, and environmental stewardship.

Conclusion

This one-year, on-farm N rate trial study compared different in-season N rates, including a sensor-based VRN approach on their effect on cotton lint yield, profitability, and nitrogen use efficiency. Overall, we found that sensor-based VRN was able to optimize profit and PFP_N, although it was not able to optimize lint yield. If similar results can be demonstrated in other sites and years, these can be persuasive to growers who judge profitability and environmental stewardship as the most important metrics in their operation. This study is limited in scope due to representing a single site and year, and therefore more environments should be tested under similar treatment combinations. Future studies conducted under Georgia conditions are important to better elucidate the potential of VRN in the state and its impact on growers and the environment.

References

Boydell, B., & McBratney, A. B. (2002). Identifying Potential Within-Field Management Zones from Cotton-Yield Estimates. *Precision Agriculture*, *3*(1), 9–23. https://doi.org/10.1023/A:1013318002609

Pisani, O., Strickland, T. C., Hubbard, R. K., Bosch, D. D., Coffin, A. W., Endale, D. M., & Potter, T. L. (2017). Soil nitrogen dynamics and leaching under conservation tillage in the Atlantic Coastal Plain, Georgia, United States. *Journal of Soil and Water Conservation*, *72*(5), 519–529. https://doi.org/10.2489/jswc.72.5.519

Pokhrel, A., Snider, J. L., Virk, S., Sintim, H. Y., Hand, L. C., Vellidis, G., Parkash, V., Chalise, D. P., & Lee, J. M. (2023). Quantifying physiological contributions to nitrogen-induced yield variation in field-grown cotton. *Field Crops Research*, *299*, 108976. https://doi.org/10.1016/j.fcr.2023.108976

Scheer, C., Rowlings, D. W., Antille, D. L., De Antoni Migliorati, M., Fuchs, K., & Grace, P. R. (2023). Improving nitrogen use efficiency in irrigated cotton production. *Nutrient Cycling in Agroecosystems*, *125*(2), 95–106. https://doi.org/10.1007/s10705-022-10204-6

Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. (n.d.). *Web Soil Survey*.

Stamatiadis, S., Schepers, J. S., Evangelou, E., Glampedakis, A., Glampedakis, M., Dercas, N., Tsadilas, C., Tserlikakis, N., & Tsadila, E. (2020). Variable-rate application of high spatial resolution can improve cotton N-use efficiency and profitability. *Precision Agriculture*, *21*(3), 695–712. https://doi.org/10.1007/s11119-019-09690-6

Stefanini, M., Larson, J. A., Lambert, D. M., Yin, X., Boyer, C. N., Scharf, P., Tubaña, B. S., Varco, J. J., Dunn, D., Savoy, H. J., & Buschermohle, M. J. (2019). Effects of optical sensing based variable rate nitrogen management on yields, nitrogen use and profitability for cotton. *Precision Agriculture*, *20*(3), 591–610. https://doi.org/10.1007/s11119-018-9599-9

The University of Georgia. (2022). *Georgia Farm Gate Value Report* (AR-22-01). https://caed.uga.edu/content/dam/caes-subsite/caed/publications/annual-reports-farm-gate-value-reports/2021_GeorgiaFGVReportDec2022%20(1).pdf

USDA-NASS. (2024). *Quick Stats*. https://quickstats.nass.usda.gov/

Yu, J., Yin, X., Raper, T. B., Jagadamma, S., & Chi, D. (2019). Nitrogen Consumption and Productivity of Cotton under Sensor-based Variable-rate Nitrogen Fertilization. *Agronomy Journal*, *111*(6), 3320–3328. https://doi.org/10.2134/agronj2019.03.0197