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# Crop physiological considerations for combining variable-density planting to optimize seed costs and weed suppression

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## Research Article

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## Abstract

High crop densities are valuable to increase weed suppression, but growers might be reluctant to implement this practice due to increased seed cost. Because it is also possible to lower planting densities in areas with no or low weed interference risk, the area allocated to each planting density must be optimized considering seed cost and productivity per plant. In this study, the growth and yield of maize (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and soybean [*Glycine max* (L.) Merr.] were characterized in response to low planting densities and arrangements. The results were used to develop a bioeconomic model to optimize the area devoted to high- and low-density plantings to increase weed suppression without increasing seed cost. Physiological differences seen in each crop varied with the densities tested; however, maize was the only crop that had differences in yield (per area) between densities. When a model to optimize low and high planting densities was used, maize and cotton showed the most plasticity in yield per planted seed (g seed$^{-1}$) and area of low density to compensate for high-density area unit. Maize grown at 75% planting density compared with the high-planting density (200%) increased yield (g seed$^{-1}$) by 229%, return by 43%, and profit by 79% while decreasing the low-density area needed to compensate for high-density area. Cotton planted at 25% planting density compared with the 200% planting density increased yield (g seed$^{-1}$) by 1,099%, return by 46%, and profit by 62% while decreasing the low-density area needed to compensate for high-density area. In contrast, the high morphological plasticity of soybean did not translate into changes in area optimization, as soybean maintained return, profit, and a 1:1 ratio for area compensation. This optimization model could allow for the use of variable planting at large scales to increase weed suppression while minimizing costs to producers.

## Introduction

Spatial distribution of weeds depends on many factors, including seed dispersal strategy, growing requirements (Benvenuti 2007), and machinery movement throughout the field (Maxwell and Ghersa 1992). In agricultural fields, weeds tend to exhibit aggregated distributions, especially those species that lack wind seed dispersal (Colbach et al. 2000; Goudy et al. 2001; Wilson and Brain 1991). In row-crop systems, such aggregation generates not only weedy patches, but also leaves fields with relatively low weed density or even weed-free areas (Thornton et al. 1990) (Figure 1A). If a weed survives in-season weed control and reproduces, it is likely to form a patch, because seeds are more likely to fall in proximity to the mother plant. The probability of finding progeny decreases rapidly as distance from the mother plant increases (Cardina et al. 1995). Over time, if weed control is not sufficiently effective, those weed patches will likely increase in density and size, which will consequently increase the probability of weed control escapes. In this way, weed patches can perpetuate themselves unless weed control intensity is increased and/or reproduction potential of surviving weeds is decreased. For example, annual ryegrass (*Lolium rigidum* Gaudin) exhibits aggregated patterns and has the ability to create large patches in agricultural fields (Gonzalez-Andujar and Saavedra 2003), which becomes costly for producers in both in-season management and crop yield loss. Weeds in these agricultural systems are the costliest pest to the producer (Oerke 2006), amounting to $24 billion in losses and damages and another $3 billion in control costs (Pimentel et al. 2005).

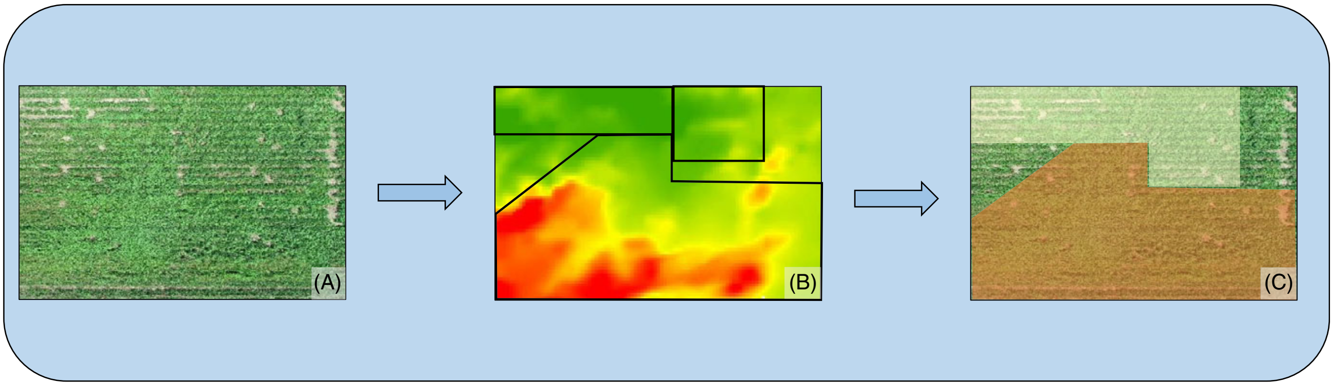


**Figure 1.** Schematic representation of (A) an aerial image using an unmanned aerial vehicle (UAV) to scout fields in year 1, (B) detection of areas of high (orange) and low (yellow) weed density in year 1, and (C) implementation of year 1 weed maps to calibrate precision planter to plant in high (red) and low (green) crop densities in year 2.

Detection and mapping of weed patches in agricultural fields using traditional scouting techniques can be challenging and time-consuming. During the growing season, producers might not always have time to scout for weed escapes. When weed scouting does occur, producers go quickly through the field and have limited vantage points, especially when scouting from a tractor, roadside, or field entrances, and may not truly capture the distribution of weed populations throughout the field (Robinson et al. 2007). For research, intensive grid sampling (by dividing large fields into many 6 m by 6 m squares on a grid) is used to quantify weed density or cover (Colbach et al. 2000; Goudy et al. 2001), but this method also takes a considerable time to collect and analyze data, which is impractical for commercial purposes. One potential alternative to traditional scouting is the use of small unmanned aerial systems (UAS), which have been developed to have low operational costs, high spatial and temporal resolution, and flexibility in image processing (Zhang and Kovacs 2012). The spatial resolution of unmanned aerial vehicles (UAVs), when set at the correct flying altitude, could provide discrimination of weed patches within agricultural fields (Castaldi et al. 2017), allowing producers to obtain quick and efficient data about the spatial distribution of weeds at large scales (Figure 1A).

Having weed patches mapped in the field opens the possibility to implement actions to suppress the growth and reproduction of individuals escaping traditional weed control. One strategy to do this is increasing crop population density to favor weed suppression (Arce et al. 2009; Mahoney et al. 2020; Teasdale 1998). Increasing crop densities can reduce the light available to weeds (Teasdale 1995) and mitigate the impact of weed escapes (Yelverton and Coble 1991), while potentially protecting crop yield (Ethridge et al. 2022; Kremer and Deichman 2014). Although the value of planting high densities has been extensively demonstrated (Adams et al. 2019; Arce et al. 2009; Widdicombe and Thelen 2002; Yelverton and Coble 1991), this practice has the downside of increasing production costs, especially for crops with expensive seed, which could discourage growers from adopting it (Gwathmey et al. 2011). However, the extra seed cost can be minimized by only implementing this practice where weedy patches exist (Figure 1B). Although many studies increase crop densities by reducing row spacing, this creates complications due to cultivation and harvest requirements. Conversely, increasing crop densities within rows reduces the amount of new equipment needed in comparison to manipulating row spacing (Johnson et al. 1998). In addition, it has been demonstrated that row spacing and planting density influence yield by determining the light distribution and interception through the canopy (Li et al. 2021). Optimal planting density and the use of heterogeneous planting arrangements, which include both high and low densities in a single field creating different light environments within the canopy (Ethridge et al. 2022), should be explored further as a strategy for maximizing yield and increasing weed suppression without creating a need for new farming equipment. Modern precision planters with GPS technology, which are currently being acquired and used by growers, can increase and decrease seeding rate within the field in real-time depending on the history of weed distribution in previous growing seasons and can control seeding rate per row (Virk et al. 2019) (Figure 1C).

The increase in seed cost when planting at high densities can represent the main challenge for adoption, depending on the amount of extra seed used and the per unit cost; thus, increasing crop density could reduce profits (Murphy et al. 1996). However, it is important to remember that one of the critical factors determining the risk of weed escapes is seedbank density and patch stability (Van Acker 2009). Thus, areas that have not exhibited consistent or dense weed patches, as determined through historical mapping, can be considered as having a low risk of weed escapes under conventional weed management. These low-risk areas can be targeted to offset the seed costs associated with high crop density areas. Therefore, we propose the use of low-density plantings in weed-free or low-risk areas.

Optimization of this variable planting strategy requires a balance between the area to be planted at high density for weed suppression and the area to be planted at low density such that there is no increase in overall seed cost for the producer. Changes in productivity as a function of planting density are usually not linear. In a previous study, doubling plant populations did not reduce the productivity of each plant by half, as determined for cotton (*Gossypium hirsutum* L.), maize (*Zea mays* L.), and soybean [*Glycine max* (L.) Merr.] (Ethridge et al. 2022). Furthermore, if the crop population density is reduced by half, the productivity per plant does not double or have a proportional response, as demonstrated in a previous study in which soybean grown at 123,550 plants ha$^{-1}$ and 432,430 plants ha$^{-1}$ had similar yields (Dunphy 2018). For this reason, it is important to account for changes in productivity per plant when using high- and low-density plantings. Considering seed costs, productivity per individual plant, and projected crop prices allows estimating the area needed at low density to compensate for the extra seed cost or to create a more productive system that reduces weed growth in areas of high density and maximizes productivity in weed-free areas.

Before using variable planting for weed suppression, it is critical to first study crop morphological and yield responses to low-density planting arrangements and then understand how these low-density plantings can complement high-density areas to optimize seed costs and maximize yield and returns. Therefore, the objectives of the present study were (1) to characterize the growth and yield responses of cotton, maize, and soybean to low-density planting arrangements; and (2) to develop a bioeconomic model that optimizes the area devoted to each density. Our hypotheses were that (1) low-density plantings will increase yield per plant and compensate for higher seed costs when using high-density crop planting densities in specific areas of the field, and (2) crop response to planting arrangements will depend on whether the density changes occur uniformly in every single row or in rows with different densities that create canopies with more dynamic light-interception patterns.

## Materials and Methods

### Site Description

A field study was conducted to evaluate growth and yield responses of different planting arrangements in maize, cotton, and soybean. This experiment was conducted in the 2019 and 2020 summer seasons at the Upper Coastal Plain Research Station in Rocky Mount, NC, USA (35.89°N, 77.68°W) and in 2020 at the Cherry Research Farm in Goldsboro, NC, USA (35.38°N, 78.03°W). Soil in Rocky Mount was a Norfolk loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudults) with pH 6.3 and 1.5% organic matter. Soil in Goldsboro was a Wickham loamy sand (fine-loamy, mixed, semiactive, thermic Typic Hapludults) with pH 5.5 and 1.25% organic matter. In 2019, the maize hybrid was DKC62-08 (Dekalb hybrid seed, Monsanto, St. Louis, MO, USA), and due to seed availability limitations, in 2020, the hybrid was DKC67-42 (Dekalb hybrid seed, Monsanto). Both hybrids belonged to the same groups for maturity (112 to 117 days), height (medium), planting rate (medium low), and ear placement (medium) (https://www.dekalbasgrowdeltapine.com/en-us/seed-finder/corn/product-detail.html, accessed June 25, 2022). In both years, the cotton cultivar was DP1646 B2XF (Bollgard® XtendFlex®, Acceleron, Bayer CropScience LP. St. Louis, MO, USA), and the soybean variety was C25947LL (Credenz®, BASF, Florham Park, NJ, USA). Crops were planted with a four-row planter (John Deere 1700, Deere & Company, Moline, IL, USA) in 91-cm rows in Rocky Mount and with a six-row planter (1215 Rigid Mounted, CNH Industrial America, Burlington, IA, USA) in 76-cm rows in Goldsboro. In each year, six treatments per crop were arranged in a randomized complete block design, with three replications in Rocky Mount and four replications in Goldsboro. In Rocky Mount, the plot size was 9.1 m (length) by 7.3 m (width) (i.e., eight rows); and in Goldsboro, the plot size was 9.1 m by 4.6 m (i.e., six rows). The number of rows per plot was intended to reduce the risk of border effects and their influence on responses to planting arrangements in the area where data were collected.

### Treatments and Management

Each crop had six planting arrangements: (1) normal density in all rows as the control, (2) 75% of normal density planting in all rows, (3) 50% of normal density planting in all rows, (4) 25% of normal density planting in all rows, (5) a sequential arrangement of alternating 25% and 75% planting densities (hereafter 75-25-75-25), and (6) a 25%-75%-75%-25% pattern of planting densities (hereafter 75-25-25-75) (Table 1). The control planting density was the optimum recommended for the variety and local conditions of eastern North Carolina and the settings of the tractor-mounted planter used (Table 1).

**Table 1.** Crop densities for each planting arrangement for maize, cotton, and soybean in Rocky Mount and Goldsboro, NC, for the pooled 2019 and 2020 summer seasons.

| Location | Crop | Density | Seeding rate | Population density[a] |
|---|---|---|---|---|
| | | % | seeds $ha^{-1}$ | plants $ha^{-1}$ |
| Rocky Mount | Maize | 100 | 71,759 | 63,069 |
| | | 75 | 53,820 | 48,438 |
| | | 50 | 35,880 | 31,049 |
| | | 25 | 17,940 | 15,523 |
| | Cotton | 100 | 99,359 | 71,759 |
| | | 75 | 71,759 | 53,820 |
| | | 50 | 49,678 | 35,880 |
| | | 25 | 24,839 | 17,940 |
| | Soybean | 100 | 210,704 | 179,399 |
| | | 75 | 155,691 | 134,549 |
| | | 50 | 103,794 | 89,699 |
| | | 25 | 51,897 | 44,850 |
| Goldsboro | Maize | 100 | 53,836 | 51,667 |
| | | 75 | 40,231 | 38,750 |
| | | 50 | 26,183 | 25,833 |
| | | 25 | 12,973 | 12,917 |
| | Cotton | 100 | 99,119 | 86,111 |
| | | 75 | 75,797 | 64,583 |
| | | 50 | 49,421 | 43,056 |
| | | 25 | 24,711 | 21,528 |
| | Soybean | 100 | 217,915 | 172,223 |
| | | 75 | 156,761 | 129,167 |
| | | 50 | 105,020 | 86,111 |
| | | 25 | 52,510 | 43,056 |

[a]Population density was determined at 3 wk after planting.

In Rocky Mount, cotton and soybean were planted on May 8, 2019, and May 4, 2020, and maize was planted on May 8, 2019, and June 3, 2020. In 2019, nitrogen was applied at 157 kg $ha^{-1}$ and 71 kg $ha^{-1}$, in maize and cotton, respectively; and in 2020, there was an increase to 208 kg $ha^{-1}$ of nitrogen in maize only. In Goldsboro, cotton, and soybean were planted on May 7, 2020, and maize was planted on June 3, 2020. In 2020, layby applications of nitrogen were applied at 157 kg $ha^{-1}$ and 86 kg $ha^{-1}$ to maize and cotton, respectively. Glufosinate (Liberty® 280 SL, Bayer CropScience LP, St. Louis, MO, USA) was applied twice in the season at 593 g ai $ha^{-1}$ on all crops in both locations to ensure control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri* S. Watson). The Rocky Mount experiment received irrigation, while the Goldsboro experiment did not. All other fertilizer, weed, and pest management practices were performed using guidelines from the NC State Extension Service and individual farms' soil test analysis results.

### Data Collection and Analysis

Stand counts were conducted at 4 wk after planting to ensure correct planting density. Crop height, width, and leaf area index (LAI, determined with a plant canopy analyzer: LAI-2200C, LI-COR Biosciences, Lincoln, NE) were measured at three points in time during the growing season, all occurring before canopy closure. Measurements were taken from the center two rows. In uniform-density planting arrangements, three plants were randomly selected from each of the center two rows for data collection. For the 75-25-75-25 and 75-25-25-75 planting arrangements, three plants from a 25% row and three plants from a 75% row were measured. For height and width measurements, six observations in total were taken per plot. Width measurements were taken from directly above the apical meristem of the main stem and measuring outward toward the row center to the longest point from the plant, and then doubled. This was done without extending leaves of the plant to ensure that the width was representative of the area covered by the plant. LAI was measured following instructions from the LAI-2200C Plant Canopy Analyzer Instruction Manual (LI-COR Biosciences) and Strachan et al. (2005). A 90° view cap was used to avoid shading from the evaluator, and below-canopy measurements were made within and between the two center rows. One above-canopy reading was taken before in-row measurements were made. In total, nine LAI measurements were taken, three for each center row and three for between the center rows. Scatter corrections were made using the FV2200 software (LI-COR Biosciences). Once the fastest-growing treatment exhibited canopy closure (i.e., at least 30% overlap between the leaves of contiguous rows), six plants were collected per plot (with the same sampling method as height and width measurements). The six plants collected were then measured for the leaf area using a leaf area meter (model LI-3100C, LI-COR Biosciences), and biomass was determined after drying plants at 55 C until a constant weight was achieved. At the end of the season, the center four rows were harvested with a spindle picker for cotton and a grain combine for maize and soybean.

Data from the 75% and 25% rows for the 75-25-75-25 and 75-25-25-75 treatments were averaged for the analysis to allow comparisons with the uniform-planting treatments. All statistical analyses were conducted separately per crop and performed using SAS v. 9.4 (SAS Institute, Cary, NC). Treatments were considered fixed effects, and block was considered a random effect in the ANOVA. Because only Rocky Mount had 2 yr of data, locations were separated in the analysis in order to have balanced data. For Rocky Mount, year was considered a fixed effect in the ANOVA model. Height, width, and LAI were analyzed with repeated measures using PROC GLIMMIX, with days after planting (DAP) as the repeated measure. For simplification and clarity, only results from the third reading (83 DAP) are presented. Biomass, leaf area, leaf number, maize ear weight, maize ear length, maize kernel count, and yield were analyzed with ANOVA using PROC GLIMMIX. Means separation was conducted using Tukey's honestly significant difference with $\alpha = 0.05$.

### *Optimization of Planting Density*

A bioeconomic model was generated to evaluate the profitability of using variable-density planting strategies by optimizing the area needed under low-density plantings to compensate for the increase in seed cost resulting from the high-density planting. The high-density planting was set at 200% using data generated by Ethridge et al. (2022) for the same locations and years and was intended to use equal row spacing while increasing planting densities to improve crop weed suppression as part of an integrated weed management strategy. Maize, cotton, and soybean seed cost and financial returns based on yield were obtained from the North Carolina State University Agricultural and Resource Economics (2021) Enterprise Budgets, using production costs for conventional tillage. According to the Enterprise Budgets, maize, cotton, and soybean seed costs were \$2.66, \$2.11, and \$0.40 per 1000 seeds, respectively. The prices for maize grain, cotton lint, and soybean grain were \$0.18, \$1.52, and \$0.38 kg$^{-1}$, respectively. To calculate the area (in hectares) of low density needed to compensate for 1 ha of high-density planting, the following model was used:

$$A_L = \frac{Y_L * S_L * R_L}{Y_H * \frac{S_H}{A_H} * R} \quad [1]$$

where $Y$ is the yield in grams per individual seed for a given planting density ($S$; seeds ha$^{-1}$), $A$ is the total area at a given planting density in hectares, and $R$ is the return, in dollars per seed (\$ seed$^{-1}$), for either the high ($H$; 200%) or the low ($L$) planting density (i.e., 100%, 75%, 50%, 25%). Yield was measured in grams per planted seed; return was the dollar amount received for each kilogram of product harvested; and profit was the return, in dollars, subtracted by the cost, in dollars. To calculate the low-density area to compensate for the high-density planting, the high-density area was set at 1 ha (Figure 2). The optimal low-density planting was chosen based upon the maximization of yield per planted seed, profit, and amount of area needed to be planted at low density to compensate for the high-density planting (Figure 2). Yield, return, profit, and area of low density to compensate for area at high density were analyzed with ANOVA using PROC GLIMMIX. Treatment means separation was conducted using Tukey's honestly significant difference with $\alpha = 0.05$.

## Results and Discussion

### *Maize*

At Rocky Mount in 2019, the 25% and 75-25-75-25 planting densities were 11% to 13% taller compared with the control (Tables 2 and 3). At Rocky Mount and Goldsboro in 2020, all treatments had greater height than the control (Tables 2 and 3). Also, in 2020, both locations presented a 10% increase in width for 75-25-75-25 and 75-25-25-75 planting densities compared with the control (Tables 2 and 3). There were no differences in leaf number per plant at canopy closure for either location (Table 4). In Rocky Mount, years were separated due to an interaction with planting arrangement. In 2019, 25%, 75-25-75-25, and 75-25-25-75 planting densities had 59%, 9%, and 23% greater leaf area at canopy closure, respectively, compared with the control (Table 5). In 2020, the 75-25-25-75 planting density had an increase in leaf area of 22% compared with the control (Table 5). There was no difference in leaf area at canopy closure at the Goldsboro location (Table 4). At both locations, maize LAI was reduced in the 25% and 75-25-75-25 planting densities compared with the control (Tables 4 and 5).

In Rocky Mount, planting density determined maize biomass and yield similarly in both years (Table 6) For example, the 25% planting density had the greatest biomass per plant at canopy closure, with increases in plant biomass of 141% compared with the control (Table 7). However, on a per area basis, the 25% planting density had decreased biomass accumulation at canopy closure, with a reduction of biomass of 43% compared with the control (Table 7). Furthermore, the 100% and 75% planting densities had 55% and 62% greater yields, respectively, than the 25% planting density (Table 7). In Goldsboro, no differences in biomass per plant were seen, but the biomass per area of the 25% planting density was decreased by 63% compared with the control (Tables 6 and 7).

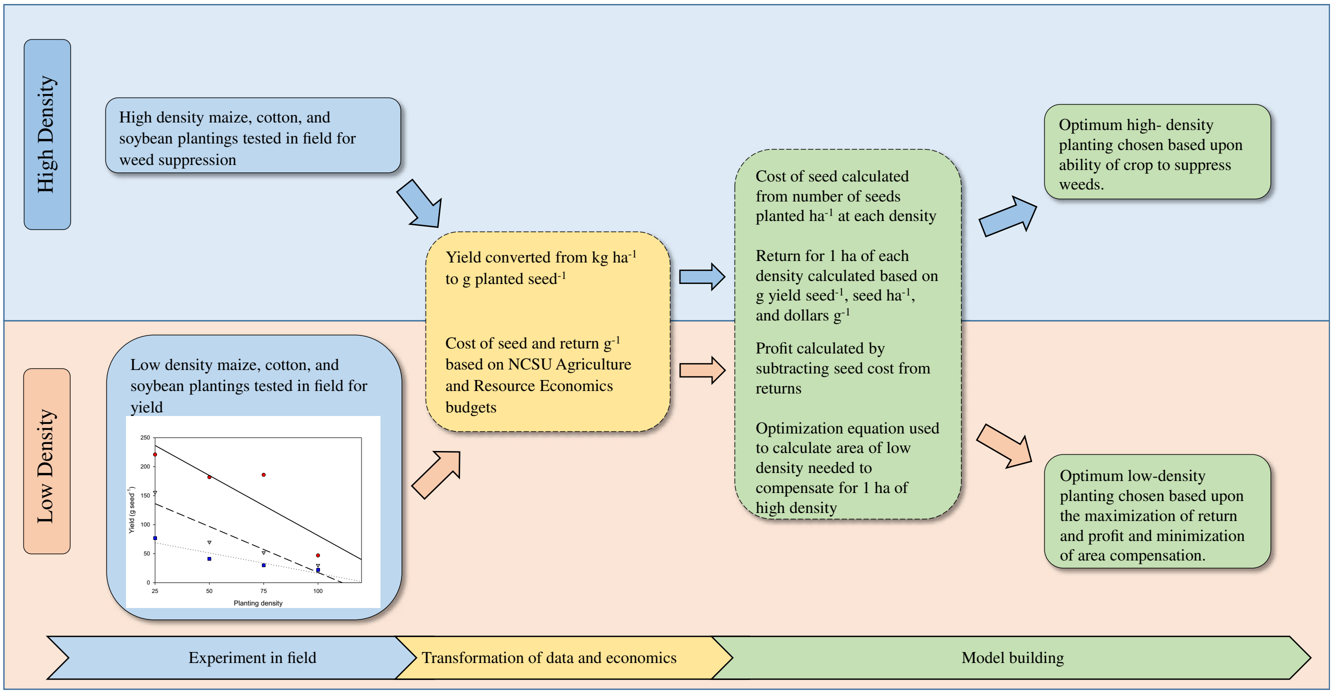


**Figure 2.** Schematic diagram representing the workflow process of the area planting optimization model. The graph on the bottom left corresponds to low-density planting yields of maize (red circles, solid line, $y = 288.5 - 2.07x$), cotton (gray triangles, dashed line, $y = 176 - 1.58x$), and soybean (blue squares, dotted line, $y = 86.5 - 0.70x$) in g seed$^{-1}$.

In Rocky Mount, the 25% and 75-25-75-25 planting densities had 56% and 45%greater maize ear weight, respectively, than the control (Tables 8 and 9). Maize ear length was also increased in the 25% and the 75-25-75-25 planting densities by 40% and 26%, respectively, compared with the control (Table 9). Maize ear weights were also increased in the 25% and the 75-25-75-25 planting densities, having increases of 59% and 46%, respectively, compared with the control (Table 9).

The results demonstrated that maize morphology and yield had an overall nonplastic response to planting densities. The stress of intraspecific competition could be contributing to negative growth responses when increasing planting density, such as those exhibited in leaf area per plant (Tollenaar et al. 1994) and plant biomass (Raymond et al. 2009). However, maize grain yield was reduced at the lowest planting density, as seen in previous studies (Hashemi-Dezfouli et al. 2005), and yield was maximized at 75% planting density. In the future, it would be beneficial to experiment with different hybrids and corresponding maturities (Ford and Mt. Pleasant 1994; Maddonni et al. 2001; Turgut et al. 2005) to understand the role of plasticity of plant architecture in the response to variable planting arrangements and weeds on yield of maize. This information could be used to select cultivars or hybrids that will exhibit a desirable response to the planting arrangement, thus increasing competitive ability when planted in high densities (Murphy et al. 1996; So et al. 2009) in weedy areas and/or to maximize yield at low densities.

## Cotton

No major differences were seen in cotton height at Rocky Mount or Goldsboro (Tables 2 and 3). At Rocky Mount, cotton width was greatest in the 75-25-75-25 planting density, with an increase of 16% compared with the control (Table 3). At Goldsboro, the 75-25-75-25 and 50% planting densities showed increases in width of 9% compared with the control (Table 3). There were no differences in leaf number per plant due to planting arrangement at either location (Table 4). At Rocky Mount, no differences were seen in leaf area per plant due to planting arrangement; however, at Goldsboro, the 75-25-25-75 had an increase of 94% compared with the control and 74% compared with the 75% planting density (Tables 4 and 5). The LAI at Rocky Mount and Goldsboro did not differ among treatments (Tables 4 and 5). Neither cotton yield nor biomass per plant at canopy closure was affected by planting arrangement (Table 6). However, total cotton biomass per area basis was decreased in the 25%, 75-25-75-25, and 75-25-25-75 planting arrangements, with reductions ranging from 47% to 77% (Table 7).

Cotton plant width increased for lower-density treatments (Table 3), mainly due to increased lateral branching (Adams et al. 2019). In cotton, no yield differences were seen in this study, likely due to increased supplemental fruiting site production on additional main stem nodes and monopodial branches when densities were decreased (Bednarz et al. 2000). Also, the fact that there were no differences in per-plant biomass could indicate a high compensatory growth response to lowering plant populations, as seen in certain varieties, such as ST4498, when plant densities ranged from 62,300 plants ha$^{-1}$ to 130,600 plants ha$^{-1}$ (Kaggwa-Asiimwe et al. 2013). In the present study, the phenotypic plasticity of cotton allowed plants to compensate in growth and yield at low densities, which should be considered when optimizing the use of a high- and low-density planting strategy.

## Soybean

At Rocky Mount and Goldsboro, the 50%, 25%, 75-25-75-25, and 75-25-25-75 planting densities exhibited decreases in height ranging from 10% to 22% compared with the control (Tables 2 and 3). At Rocky Mount, the 50% planting density caused a reduction in

**Table 2.** ANOVA for maize, cotton, and soybean height and width at 83 d after planting in response to planting arrangement (P), year (Y), and their interaction (P × Y) at Rocky Mount, NC, in 2019 and 2020 and Goldsboro, NC, in 2020.

| Location | Crop | Effect | Height | Width |
|---|---|---|---|---|
| Rocky Mount | Maize | P | <0.0001 | 0.002 |
| | | Y | <0.0001 | <0.0001 |
| | | P × Y | 0.001 | 0.0002 |
| | Cotton | P | 0.05 | <0.0001 |
| | | Y | <0.0001 | <0.0001 |
| | | P × Y | 0.28 | 0.40 |
| | Soybean[a] | P | 0.01 | 0.39 |
| | | Y | n.d. | n.d. |
| | | P × Y | n.d. | n.d. |
| Goldsboro | Maize | P | 0.0002 | 0.007 |
| | Cotton | P | 0.69 | 0.005 |
| | Soybean | P | 0.0003 | 0.014 |

[a]No data available for Rocky Mount 2020 soybean due to vertebrate pest damage.

**Table 3.** Height and width measurements for maize, cotton, and soybean at 83 d after planting for each planting density at Rocky Mount, NC, in 2019 and 2020 and Goldsboro, NC, in 2020.[a]

| Location | Crop | Planting density | Height | | Width | |
|---|---|---|---|---|---|---|
| | | % | cm | | | |
| | | | 2019 | 2020 | 2019 | 2020 |
| Rocky Mount[b] | Maize | 100 | 179 ± 5 c | 197 ± 7 b | 96 ± 1 ab | 100 ± 2 c |
| | | 75 | 179 ± 5 c | 211 ± 7 a | 90 ± 1 b | 108 ± 2 abc |
| | | 50 | 185 ± 5 c | 219 ± 7 a | 90 ± 1 b | 102 ± 2 c |
| | | 25 | 206 ± 6 a | 213 ± 7 a | 106 ± 1 a | 104 ± 2 bc |
| | | 75-25-75-25 | 200 ± 6 ab | 214 ± 7 a | 106 ± 1 a | 112 ± 2 a |
| | | 75-25-25-75 | 191 ± 5 bc | 216 ± 7 a | 96 ± 1 ab | 110 ± 2 ab |
| | Cotton | 100 | 86 ± 2 ab | | 74 ± 1 bcd | |
| | | 75 | 89 ± 2 ab | | 68 ± 1 d | |
| | | 50 | 88 ± 2 ab | | 78 ± 1 b | |
| | | 25 | 93 ± 2 a | | 78 ± 1 bc | |
| | | 75-25-75-25 | 93 ± 2 a | | 88 ± 1 a | |
| | | 75-25-25-75 | 83 ± 2 b | | 70 ± 1 cd | |
| | Soybean | 100 | 77 ± 2 a | | 72 ± 1 a | |
| | | 75 | 72 ± 2 ab | | 66 ± 1 ab | |
| | | 50 | 64 ± 1 bc | | 60 ± 1 b | |
| | | 25 | 60 ± 1 c | | 66 ± 1 ab | |
| | | 75-25-75-25 | 66 ± 1 bc | | 64 ± 1 ab | |
| | | 75-25-25-75 | 66 ± 2 bc | | 64 ± 1 ab | |
| Goldsboro | Maize | 100 | 197 ± 3 b | | 100 ± 2 c | |
| | | 75 | 211 ± 4 a | | 108 ± 1 abc | |
| | | 50 | 219 ± 3 a | | 102 ± 1 c | |
| | | 25 | 213 ± 2 a | | 104 ± 2 bc | |
| | | 75-25-75-25 | 214 ± 3 a | | 112 ± 2 a | |
| | | 75-25-25-75 | 216 ± 3 a | | 112 ± 1 ab | |
| | Cotton | 100 | 75 ± 2 a | | 64 ± 1 b | |
| | | 75 | 77 ± 2 a | | 60 ± 1 b | |
| | | 50 | 79 ± 2 a | | 70 ± 1 a | |
| | | 25 | 77 ± 2 a | | 66 ± 1 ab | |
| | | 75-25-75-25 | 80 ± 2 a | | 70 ± 1 a | |
| | | 75-25-25-75 | 76 ± 2 a | | 64 ± 1 b | |
| | Soybean | 100 | 68 ± 2 a | | 72 ± 1 a | |
| | | 75 | 66 ± 2 a | | 70 ± 1 ab | |
| | | 50 | 61 ± 1 b | | 64 ± 1 bc | |
| | | 25 | 57 ± 1 b | | 62 ± 1 c | |
| | | 75-25-75-25 | 60 ± 1 b | | 66 ± 1 abc | |
| | | 75-25-25-75 | 60 ± 2 b | | 62 ± 1 c | |

[a]Means followed by the same letter within column and crop were not statistically different based on Tukey's honestly significant difference ($\alpha = 0.05$).
[b]Years were separated for Rocky Mount variables where treatment and year interactions were significant. If no interaction occurred, then an average of 2019 and 2020 data is presented.

width of 17% compared with the control (Tables 2 and 3). At Goldsboro, the 50%, 25%, and 75-25-25-75 planting densities had decreased width compared with the control, ranging from 11% to 14% (Tables 2 and 3). In Rocky Mount, soybean leaf number at canopy closure in the 25% and 75-25-25-75 planting arrangements was increased by 104% and 73%, respectively, compared with the control (Table 5). However, only the 25% planting density had increases in leaf area of 106% compared with the control (Table 5), indicating that the lower densities favored the production of more and smaller leaves. The LAI at Rocky Mount did

**Table 4.** ANOVA for maize, cotton, and soybean leaf number per plant, leaf area per plant, and leaf area index (LAI) in response to planting arrangement (P), year (Y), and their interaction (P × Y) at Rocky Mount, NC, in 2019 and 2020 and Goldsboro, NC, in 2020.

| Location | Crop | Effect | Leaf number per plant | Leaf area per plant | LAI |
|---|---|---|---|---|---|
| Rocky Mount | Maize | P | 0.46 | 0.002 | 0.0004 |
| | | Y | 0.05 | 0.02 | 0.23 |
| | | P × Y | 0.16 | 0.03 | 0.63 |
| | Cotton | P | 0.44 | 0.42 | 0.41 |
| | | Y | 0.34 | 0.36 | 0.15 |
| | | P ×Y | 0.38 | 0.37 | 0.51 |
| | Soybean[a] | P | 0.01 | 0.04 | 0.80 |
| | | Y | 0.03 | 0.02 | n.d. |
| | | P × Y | 0.70 | 0.30 | n.d. |
| Goldsboro | Maize | P | 0.70 | 0.06 | 0.01 |
| | Cotton | P | 0.13 | 0.01 | 0.84 |
| | Soybean[b] | P | n.d. | n.d. | 0.10 |

[a]No data available for Rocky Mount in 2019. Only Rocky Mount 2020 data are presented.
[b]No data available for Goldsboro 2020 soybean leaf number or leaf area.

**Table 5.** Leaf number, leaf area, and leaf area index (LAI) at 83 d after planting for maize, cotton, and soybean for each planting density at Rocky Mount, NC, in 2019 and 2020 and Goldsboro, NC, in 2020.[a]

| Location | Crop | Planting density | Leaf number | Leaf area | | LAI |
|---|---|---|---|---|---|---|
| | | % | | mm³ | | m² m⁻² |
| | | | | 2019[b] | 2020 | |
| Rocky Mount | Maize | 100 | 11 ± 0.5 a | 2,906 ± 110 d | 4,403 ± 334 b | 2.9 ± 0.2 a |
| | | 75 | 11 ± 0.7 a | 3,290 ± 142 cd | 5,495 ± 271 ab | 2.8 ± 0.2 a |
| | | 50 | 11 ±0.5 a | 3,431 ± 196 cd | 5,616 ± 201 ab | 2.2 ± 0.2 b |
| | | 25 | 11 ± 0.3 a | 4,622 ± 82 a | 5,295 ± 122 ab | 1.6 ± 0.1 c |
| | | 75-25-75-25 | 11 ± 0.2 a | 4,253 ± 227 ab | 5,104 ± 145 ab | 2.1 ± 0.1 bc |
| | | 75-25-25-75 | 11 ± 0.2 a | 3,770 ± 171 bc | 5,368 ± 180 a | 2.1 ± 0.1 bc |
| | Cotton | 100 | 97 ± 9 a | 3,777 ± 267 a | | 3.6 ± 0.3 a |
| | | 75 | 112 ± 11 a | 4,230 ± 536 a | | 2.9 ± 0.2 a |
| | | 50 | 119 ± 15 a | 4,613 ± 410 a | | 3.1 ± 0.3 a |
| | | 25 | 137 ± 17 a | 5,187 ± 535 a | | 3.7 ± 0.2 a |
| | | 75-25-75-25 | 137 ± 15 a | 5,410 ± 610 a | | 3.5 ± 0.3 a |
| | | 75-25-25-75 | 129 ± 12 a | 5,147 ± 604 a | | 2.9 ± 0.3 a |
| | Soybean | 100 | 49 ± 5 b | 2,945 ± 322 b | | 3.7 ± 0.3 a |
| | | 75 | 56 ± 4 ab | 3,109 ± 373 b | | 3.4 ± 0.3 a |
| | | 50 | 79 ± 8 ab | 4,745 ± 568 ab | | 2.9 ± 0.3 a |
| | | 25 | 100 ± 13 a | 6,057 ± 1099 a | | 2.7 ± 0.2 a |
| | | 75-25-75-25 | 82 ± 7 ab | 4,522 ± 511 ab | | 2.8 ± 0.2 a |
| | | 75-25-25-75 | 85 ± 8 a | 4,907 ± 505 ab | | 2.8 ± 0.3 a |
| Goldsboro | Maize | 100 | 10 ± 0.2 a | 4,641 ± 370 a | | 2.6 ± 0.2 a |
| | | 75 | 10 ± 0.2 a | 5,103 ± 237 a | | 2.6 ± 0.2 a |
| | | 50 | 10 ± 0.2 a | 5,145 ± 292 a | | 2.2 ± 0.2 ab |
| | | 25 | 10 ± 0.2 a | 5,383 ± 141 a | | 1.7 ± 0.1 b |
| | | 75-25-75-25 | 10 ± 0.2 a | 5,370 ± 170 a | | 1.9 ± 0.1 b |
| | | 75-25-25-75 | 10 ± 0.1 a | 5,362 ± 80 a | | 2.2 ± 0.1 ab |
| | Cotton | 100 | 69 ± 15 a | 2,886 ± 673 b | | 3.4 ± 0.3 a |
| | | 75 | 70 ± 9 a | 3,226 ± 494 b | | 2.9 ± 0.2 a |
| | | 50 | 110 ± 22 a | 4,804 ± 852 ab | | 3.3 ± 0.3 a |
| | | 25 | 114 ± 18 a | 4,985 ± 881 ab | | 3.3 ± 0.2 a |
| | | 75-25-75-25 | 117 ± 21 a | 5,131 ± 414 ab | | 3.3 ± 0.3 a |
| | | 75-25-25-75 | 123 ± 15 a | 5,598 ± 804 a | | 3.0 ± 0.3 a |
| | Soybean[c] | 100 | n.d. | n.d. | | 4.0 ± 0.3 a |
| | | 75 | n.d. | n.d. | | 4.0 ± 0.3 a |
| | | 50 | n.d. | n.d. | | 3.4 ± 0.3 ab |
| | | 25 | n.d. | n.d. | | 2.7 ± 0.2 b |
| | | 75-25-75-25 | n.d. | n.d. | | 3.2 ± 0.2 ab |
| | | 75-25-25-75 | n.d. | n.d. | | 3.1 ± 0.3 ab |

[a]Means followed by the same letter within column and crop were not statistically different based on Tukey's honestly significant difference (α = 0.05).
[b]Years were separated for variables where treatment and year interactions were significant. If no interaction occurred, then an average of 2019 and 2020 data is presented.
[c]No leaf number or leaf area data for Goldsboro, NC, 2020.

not differ among treatments (Tables 4 and 5). At Goldsboro, there was a decrease of 33% in LAI in the 25% planting density compared with the control (Tables 4 and 5). There were no differences in biomass per plant at either location (Table 6). However, at Rocky Mount, the biomass per area of the 25%, 75-25-75-25, and 75-25-25-75 planting densities had reductions ranging from

**Table 6.** ANOVA for maize, cotton, and soybean biomass and yield in response to planting arrangement (P), year (Y), and their interaction (P × Y) at Rocky Mount, NC, in 2019 and 2020 and Goldsboro, NC, in 2020.

| Location | Crop | Effect | Biomass per plant | Biomass per area | Yield |
|---|---|---|---|---|---|
| Rocky Mount | Maize | P | 0.001 | 0.02 | 0.001 |
| | | Y | 0.20 | 0.49 | 0.02 |
| | | P × Y | 0.20 | 0.30 | 0.82 |
| | Cotton | P | 0.83 | 0.0001 | 0.12 |
| | | Y | 0.33 | 0.22 | 0.24 |
| | | P × Y | 0.87 | 0.65 | 0.01 |
| | Soybean | P | 0.25 | 0.0001 | 0.01 |
| | | Y | 0.01 | 0.01 | 0.04 |
| | | P x Y | 0.79 | 0.47 | 0.01 |
| Goldsboro[a] | Maize | P | 0.43 | 0.008 | n.d. |
| | Cotton | P | 0.49 | <0.0001 | n.d. |
| | Soybean | P | 0.78 | 0.003 | n.d. |

[a]No yield data for Goldsboro, NC, 2020.

**Table 7.** Biomass and yield measurements for maize, cotton, and soybean for each planting density at Rocky Mount, NC, in 2019 and 2020 and Goldsboro, NC, in 2020.[a]

| Location | Crop | Planting density | Biomass per plant | Biomass per area | Yield | |
|---|---|---|---|---|---|---|
| | | % | g | 1,000 kg ha$^{-1}$ | | |
| Rocky Mount | Maize | 100 | 154 ± 15 c[b] | 11.1 ± 1.1 a | 8.4 ± 1.9 a | |
| | | 75 | 192 ± 16 bc | 10.3 ± 0.9 ab | 10.0 ± 1.4 a | |
| | | 50 | 227 ± 10 abc | 8.2 ± 0.4 ab | 6.6 ± 1.1 ab | |
| | | 25 | 349 ± 33 a | 6.3 ± 0.6 b | 3.8 ± 0.7 b | |
| | | 75-25-75-25 | 271 ± 30 ab | 8.4 ± 0.9 ab | 6.5 ± 1.0 ab | |
| | | 75-25-25-75 | 266 ± 28 abc | 8.2 ± 0.8 ab | 6.5 ± 1.2 ab | |
| | Cotton | 100 | 130 ± 21 a | 9.6 ± 1.5 a | 4.0 ± 0.6 a | |
| | | 75 | 127 ± 25 a | 7.0 ± 1.4 ab | 3.7 ± 0.3 a | |
| | | 50 | 130 ± 11 a | 4.8 ± 0.4 ab | 3.6 ± 0.5 a | |
| | | 25 | 158 ± 11 a | 2.2 ± 0.1 c | 3.9 ± 0.5 a | |
| | | 75-25-75-25 | 152 ± 24 a | 5.0 ± 0.8 b | 3.7 ± 0.5 a | |
| | | 75-25-25-75 | 131 ± 20 a | 4.4 ± 0.7 bc | 3.1 ± 0.3 a | |
| | | | | | 2019 | 2020 |
| | Soybean | 100 | 56 ± 14 a | 10.0 ± 2.5 a | 4.2 ± 0.7 a | 5.7 ± 0.4 a |
| | | 75 | 62 ± 13 a | 8.2 ± 1.7 ab | 4.0 ± 0.6 a | 5.2 ± 0.2 a |
| | | 50 | 68 ± 12 a | 6.1 ± 1.1 abc | 3.7 ± 0.5 a | 4.9 ± 0.3 ab |
| | | 25 | 88 ± 21 a | 3.8 ± 0.9 c | 3.3 ± 0.4 a | 4.7 ± 0.4 ab |
| | | 75-25-75-25 | 74 ± 13 a | 5.7 ± 1.1 bc | 4.0 ± 0.6 a | 5.4 ± 0.3 a |
| | | 75-25-25-75 | 82 ± 15 a | 5.3 ± 0.6 bc | 4.1 ± 0.7 a | 3.3 ± 0.6 b |
| Goldsboro[c] | Maize | 100 | 129 ± 12 a | 8.1 ± 0.6 a | | |
| | | 75 | 157 ± 30 a | 7.4 ± 1.2 a | | |
| | | 50 | 176 ± 27 a | 5.5 ± 0.7 ab | | |
| | | 25 | 191 ± 50 a | 3.0 ± 0.6 b | | |
| | | 75-25-75-25 | 177 ± 27 a | 4.9 ± 0.6 ab | | |
| | | 75-25-25-75 | 177 ± 25 a | 5.1 ± 0.8 ab | | |
| | Cotton | 100 | 116 ± 19 a | 9.0 ± 1.6 a | | |
| | | 75 | 124 ± 19 a | 7.3 ± 1.2 ab | | |
| | | 50 | 120 ± 21 a | 4.9 ± 0.9 b | | |
| | | 25 | 144 ± 18 a | 2.5 ± 0.9 c | | |
| | | 75-25-75-25 | 129 ± 13 a | 5.4 ± 1.0 b | | |
| | | 75-25-25-75 | 153 ± 19 a | 5.6 ± 1.0 b | | |
| | Soybean | 100 | 84 ± 20 a | 15.1 ± 3.4 a | | |
| | | 75 | 90 ± 16 a | 12.0 ± 2.0 ab | | |
| | | 50 | 92 ± 32 a | 8.2 ± 2.7 abc | | |
| | | 25 | 131 ± 37 a | 5.7 ± 1.6 c | | |
| | | 75-25-75-25 | 112 ± 27 a | 8.5 ± 2.5 abc | | |
| | | 75-25-25-75 | 114 ± 25 a | 7.0 ± 3.0 bc | | |

[a]Means followed by the same letter within column and crop were not statistically different based on Tukey's honestly significant difference (α = 0.05).
[b]Years were separated for variables where treatment and year interactions were significant. If no interaction occurred, then an average of 2019 and 2020 data is presented.
[c]No yield data available for Goldsboro, NC, 2020.

43% to 62%, compared with the control (Table 7). At Goldsboro, the 50%, 25%, 75-25-75-25, and 75-25-25-75 planting densities had reduced biomass per area, ranging from 38% to 73% compared with the control (Table 7). At Rocky Mount in 2019, there were no differences in yield between planting arrangements; however, in 2020, the 75-25-25-75 planting density had the lowest yield, with a reduction of 42% compared with the control (Tables 6 and 7).

Soybean had the most plastic response to planting densities in this study. Although small decreases in height were detected, previous studies have shown that row spacing (Cox and Cherney

**Table 8.** ANOVA for maize ear weight in response to planting arrangement (P), year (Y), and their interaction (P × Y) for Rocky Mount, NC, in 2019 and 2020, and for maize ear length and kernel count in response to planting arrangement (P) for Rocky Mount, NC, for 2019.

| Crop | Effect | Ear weight | Ear length | Kernel count |
|---|---|---|---|---|
| Maize | P | 0.002 | 0.001 | 0.003 |
| | Y | 0.18 | n.d. | n.d. |
| | P × Y | 0.43 | n.d. | n.d. |

**Table 9.** Maize ear length, ear weight, and kernel count measurements for each planting density at Rocky Mount, NC.[a]

| Location | Crop | Planting density | Ear weight | Ear length[b] | Kernel count[b] |
|---|---|---|---|---|---|
| | | % | g | cm | |
| Rocky Mount | Maize | 100 | 166 ± 16 b[b] | 15 ± 0.8 c | 389 ± 42 c |
| | | 75 | 201 ± 14 ab | 16 ± 0.6 bc | 427 ± 33 bc |
| | | 50 | 203 ± 15 ab | 17 ± 0.5 bc | 467 ± 28 abc |
| | | 25 | 259 ± 6 a | 21 ± 0.3 a | 618 ± 30 a |
| | | 75-25-75-25 | 240 ± 10 a | 19 ± 0.7 ab | 566 ± 30 ab |
| | | 75-25-25-75 | 219 ± 15 ab | 18 ± 1.0 abc | 477 ± 42 abc |

[a]Means followed by the same letter within column and crop were not statistically different based on Tukey's honestly significant difference (α = 0.05).
[b]Ear length and kernel count means based on 2019 data only.

**Table 10.** Optimization of planting density and seed costs for variable planting in maize, cotton, and soybean.[a]

| Crop | Planting Density | Yield | 2021 Return | Profit | Low-density area to compensate for high-density area |
|---|---|---|---|---|---|
| | % | g seed$^{-1}$ [b] | \$ ha$^{-1}$ | \$[c] | ha ha$^{-1}$ |
| Maize | 200[d] | 57 ± 2 c | 1,242 ± 49 b | 911 ± 49 bc | — |
| | 100 | 119 ± 8 bc | 1,423 ± 90 ab | 1,243 ± 90 ab | 0.76 ± 0.08 b |
| | 75 | 186 ± 25 a | 1,773 ± 242 a | 1,630 ± 242 a | 0.65 ± 0.13 b |
| | 50 | 182 ± 26 ab | 1,156 ± 167 bc | 1,060 ± 167 bc | 0.98 ± 0.17 b |
| | 25 | 221 ± 32 a | 701 ± 103 c | 654 ± 103 c | 1.58 ± 0.26 a |
| Cotton | 200 | 13 ± 2 d | 4,046 ± 634 b | 3,614 ± 634 c | — |
| | 100 | 30 ± 5 cd | 4,615 ± 788 ab | 4,405 ± 788 bc | 0.84 ± 0.08 a |
| | 75 | 52 ± 5 bc | 5,620 ± 518 a | 5,469 ± 518 ab | 0.66 ± 0.10 ab |
| | 50 | 70 ± 7 b | 5,291 ± 534 ab | 5,186 ± 534 ab | 0.70 ± 0.10 ab |
| | 25 | 156 ± 22 a | 5,887 ± 822 a | 5,835 ± 822 a | 0.62 ± 0.07 b |
| Soybean | 200 | 11 ± 1 d | 1,841 ± 211 a | 1,669 ± 211 a | — |
| | 100 | 22 ± 2 cd | 1,770 ± 182 a | 1,686 ± 182 a | 0.98 ± 0.03 a |
| | 75 | 30 ± 2 bc | 1,752 ± 107 a | 1,690 ± 107 a | 0.97 ± 0.07 a |
| | 50 | 41 ± 2 b | 1,609 ± 96 a | 1,568 ± 96 a | 1.07 ± 0.12 a |
| | 25 | 77 ± 8 a | 1,520 ± 152 a | 1,499 ± 152 a | 1.12 ± 0.10 a |

[a]Means followed by the same letter within column and crop were not statistically different based on Tukey's honestly significant difference (α = 0.05).
[b]Yield measured in grams per planted seed.
[c]Estimated costs and returns based upon North Carolina State University Agricultural and Resource Economics (2021) Enterprise Budgets for conventional tillage maize, cotton, and soybean.
[d]The 200% planting density data is based upon data from Ethridge et al. (2022).

2011) or cultivars (Parvez et al. 1989) could be more influential in changing the architecture of the plant, including traits such as height and width. Furthermore, similar to the results at the Goldsboro location, it has been reported that increasing plant population also increases LAI, as seen with increases from 7,660 plants ha$^{-1}$ to 22,733 plants ha$^{-1}$ (Hicks et al. 1969). Soybean yield is relatively insensitive to plant population due to the ability of this crop to compensate over a wide range of seeding rates (Dunphy 2018). In addition, newer cultivars have maximum yield thresholds at populations of approximately 230,000 plants ha$^{-1}$ (DeBruin and Pedersen 2009), which was not achieved in this study.

### Optimization of Planting Density

For this model, because no differences in yield were seen between the 50, 75-25-75-25, and 75-25-25-75, these treatments were combined to represent 50% planting density.

In maize, yield (in grams per planted seed) was highest in the 75%, 50%, and 25% planting densities (Table 10). The 75% density increased yield by 229%, the 50% density increased yield by 221%, and the 25% density increased yield by 290% compared with the 200% planting density (Table 10). However, only the 75% planting density had an increased return of 43% and increased profit of 79% compared with the 200% planting density (Table 10). The 25% planting density had a decrease in returns of 44%, although the profits were similar to the 200% treatment (Table 10). The 50% planting density showed no differences in return or profit compared with the 200% (Table 10). The 100%, 75%, and 50% planting densities required similar areas to compensate for the extra costs associated with the area planted at 200% density (Table 10). However, the 25% planting density would need 52% more area to compensate for each hectare planted at 200% density (Table 10).

In cotton, the 75%, 50%, and 25% planting densities had higher yields (in grams per planted seed) than the 200% planting density

(Table 10). The 75% density increased yield by 296%, the 50% density increased yield by 439%, and the 25% density increased yield by 1,099% compared with the 200% planting density (Table 10). Only the 75% and 25% planting densities had increased returns compared with the 200% planting of 39% and 46%, respectively (Table 10). However, the 75%, 50%, and 25% planting densities had higher profits compared with the 200% planting arrangement, with increases of 51%, 44%, and 62%, respectively (Table 10). The treatment with the lowest area needed to compensate for 1 ha of 200% density planting was the 25% density planting, needing 26% less area (Table 10).

In soybean, the 75%, 50%, and 25% planting densities had higher yields (in grams planted per seed) than the 200% planting density (Table 10). The 75%, 50%, and 25% planting densities increased yield by 163%, 263%, and 586%, respectively, compared with the 200% planting density (Table 10). However, there were no differences among planting densities for return, profit, or area of low density needed to compensate for 1 ha of 200% density (Table 10).

The viability of planting strategies and optimization models will depend on the plasticity and ability of the crop to respond favorably to the changes in planting densities. Thus, when using variable and heterogeneous planting densities as an integrated weed management strategy, both tolerance to increased intraspecific competition under high densities and increased yield per individual at low densities will be critical to optimize each model and choose the best planting densities.

The optimization of planting densities in maize, cotton, and soybean proposed in this study could allow for variable planting to increase weed suppression without additional seed costs to the producer. Due to the morphological and physiological plasticity of certain crops, growth compensatory mechanisms at low densities allow plants to modify their canopy architecture and increase productivity per plant. For example, the high plasticity of soybean under various planting densities (de Luca et al. 2014) made it possible to reduce plant density to 25% of normal in areas of low weed pressure to compensate for high-density planting for weed suppression, without sacrificing overall yield and profits. In the present study, this plasticity permitted a 1:1 ratio of low- to high-density areas (Table 10). In cotton, there was potential to use less area under low-density plantings due to this crop's ability to increase yield per planted seed at the low densities (Table 10) by increasing light interception at lower leaf layers within the canopy (Board and Harville 1992; Reta-Sanchez and Fowler 2002; Stewart et al. 2003). This means that in areas of the field where weed pressure is low or zero, a grower can plant 0.62 ha of cotton at a 25% density per high-density hectare to maintain yield and seed cost, or even plant at a 1:1 area ratio and increase profits. This strategy will be important for cotton growers, as the high cost of cotton seed, seed treatments, and gene technology makes it imperative to maintain or reduce costs (Gwathmey et al. 2011).

Crops that exhibit minimal changes in shoot architecture in response to planting density, such as modern maize hybrids, might need low densities closer to optimum to maintain yield. For example, the maize low-density planting that was needed to match the 200% planting density was 75%, which was also the planting density with the highest LAI. This was in addition to having the highest biomass accumulation per hectare. Furthermore, the 75% planting density had a higher yield per area basis compared with the 50% planting densities and higher yield per seed, return per hectare, and profit compared with the 200% planting density.

The relationship between the planting densities and yield is another component of this model that needs to be taken into consideration, as these relationships are not linear (Table 10). When plant density is reduced, the plant canopy becomes more open and increases the productivity per plant (Long et al. 2006). This nonlinear relationship becomes important when seed cost is included. Thus, the use of variable densities can optimize planting by avoiding seed cost increases and allowing overall yield maximization compared with a uniform planting throughout a field. In addition, although the paired rows, including the 75-25-75-25 and the 75-25-25-75 planting densities, exhibited some morphological differences, there were no differences in yield compared with the 50% planting density; therefore, heterogeneous rows are not necessary when using lower-density planting strategies to maximize yield.

Due to the differences in the low- and high-density ratios provided by the model, one next step is to understand how weed interference will affect the productivity of the crops and area allocated to each planting density. It has been shown that increasing crop planting density can favor weed suppression (Arce et al. 2009; Teasdale 1998) or mitigate the impact of weed escapes (Yelverton and Coble 1991), but it is essential to know the influence that weed competition will have on the productivity of each crop before using this method at large scales. In addition, if competition with weeds does affect the productivity of the crops, it will be necessary to integrate this new factor into the model to reflect these potential changes.

The present study created a novel approach to optimize planting densities that used a combination of high-density plantings for weed suppression and low-density plantings in weed-free areas to offset seed costs for the producer (Figure 2). This study also showed the various physiological responses and yield responses of maize, cotton, and soybean at low-density plantings. Although maize and cotton did not exhibit major changes in morphology due to planting density, yields (in grams per planted seed) were more plastic in their response to the open canopy structure. The gain in yield, in addition to the reduction in seed cost for maize and cotton at the low densities, was key for optimizing areas using high- and low-density plantings. Therefore, both maize and cotton were able to have less area designated to low-density areas when compensating for 1 ha of high-density planting. Alternatively, soybean had more plastic morphological responses to lower planting densities, but a nonplastic response to return, profit, and area of low density to compensate for 1 ha of high density. Although soybean was able to maintain a 1:1 area ratio, it did not have a clear response to the change in density that could benefit the use of this planting strategy. The use of the high- and low-density plantings in maize and cotton had a higher benefit than that of the soybean due to the seed cost and increase in yield per plant at lower densities for maize and cotton. Using area compensation ratios allowed us to take advantage of each crop's responses to low- and high-density plantings to optimize field-planting densities. With the use of UAS for field scouting and weed distribution mapping and modern precision planters, this optimization could prove beneficial to producers to increase the efficacy of their integrated weed management and maintain and even reduce costs.

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