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AGRONOMY AND SOILS

Refining Cotton Replanting Recommendations

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ABSTRACT

The decision to replant suboptimal cotton (*Gossypium hirsutum* L.) stands has become more challenging in recent years because the suggested retail price per bag of replanting seed has increased by more than 25%. Previous studies have justified replanting when ≥ 50% of planted area is occupied by skips ≥ 0.91 m (3 ft). Revision of replanting recommendations was deemed necessary with the introduction of more advanced and accurate plant and skip detection methods. The objective of this study was to update replanting recommendations using unmanned aerial vehicles (UAVs). The study was conducted at three sites in eastern North Carolina during the 2019 and 2020 growing seasons. Each site had an early- and a late-planted trial. Treatment combinations were produced using various ratios of DP 1646 B2XF and DP 493 cotton seed. Simulated replanted plots were planted with 100% DP 1646 B2XF three to four weeks after initial planting. Following emergence, glyphosate and glufosinate were applied to terminate all conventional seedlings and produce random skips. Cotton skips were detected using a Zenmuse X5 RGB sensor mounted on a UAV. Yield was regressed to the percentage of planted area occupied by skips > 0.91 m. In 2019, the replanted treatment did not yield higher than earlier planted treatments but, in 2020, yields were significantly higher in the replanted treatment compared to most earlier planted treatments. The data suggest that a replant should be triggered when 30 to 40% of the planted area is occupied by skips ≥ 0.91 m.

Cotton growers often decide to replant stands with less-than-optimal germination rates, emergence, and seed vigor primarily due to unfavorable temperature, precipitation, and soil moisture conditions. Studies have demonstrated that low temperatures and excessively wet soils during planting and germination negatively affect crop performance (Bauer and Bradow, 1996; Kittock et al., 1987; Pettigrew and Meredith Jr., 2009; Whitaker et al., 2013). In the event of a replant, growers rely on seed companies to provide replant seed. Decades ago, replant seed was covered by seed companies at no charge. But by 2013, the cost of replanting had soared to 37 to \$50 ha^{-1} (\$15-20 acre^{-1}) (Dodds, 2013). The major seed companies charged 50% of the seed cost and, in some cases, an additional technology fee for replanting seed (Dodds, 2013). Currently, there is not a clear distinction between the seed or germplasm costs and technology fees. Therefore, most seed companies are charging 25% of suggested retail price per bag of replanting seed. By 2020, the total cost of replanting had increased to approximately \$86 ha^{-1} (\$35 acre^{-1}), which included fuel, labor, and equipment usage for a seeding rate of 107,600 sd ha^{-1} (43,560 sd acre^{-1}) (Collins and Edmisten, 2019). Large acreage producers often do not have the luxury of time, or the labor resources needed, to determine if replanting is justified, so some will decide to replant a field that might not need it. The additional cost of replanting warrant methods that can justify replanting in a precise, cost effective, and timely fashion.

Researchers have made replanting recommendations based on weather patterns after planting, germination rates, planting date, skip size, and skipped area. For example, Boman and Lemon (2007) recommended delaying the replanting decision until after two to three days of good growing conditions. Dodds (2013) established that yield potentials are acceptable if more than 37,000 plants are counted in one hectare (15,000 plants in one acre) and skips of 0.61 m to 0.91 m (2 to 3 ft) remained minimal. The study also advised not to replant during the month of June. Lastly, Jost et al. (2006) supported a replant if 50% of a given planted area was occupied by skips equal to or greater than 0.91 m (3 ft). Although some studies have mentioned the importance of replanting cost when assessing a replanting decision (McQuigg et al., 1965), most have excluded the economic implications in their analyses, which might have

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led to inaccurate replanting recommendations. All studies agreed that, when in doubt of a replant, it is generally safe to not replant. Yet, in the presence of a suboptimal stand, farmers could benefit from precise and accurate replanting recommendations.

Lower plant populations, especially those with uneven plant spacing, are known to reduce yields. Evaluating plant populations helps growers quantify the success rate of emerged plants as compared to the target population and determine if a replant is necessary. Numerous studies have focused on finding differences between plant populations and deriving recommendations that can establish optimal yield results (Table 1). It can be inferred from these studies that plant populations between 15,000 and 30,000 plants ha^{-1} (6,070 and 12,140 plants acre^{-1}) do not achieve full yield potential. Butler (2019) observed no differences in yield between 49,000 and 123,000 plants ha^{-1} (19,830 and 49,777 plants acre^{-1}). All other studies using a minimum population size greater than 49,000 plants ha^{-1} (19,830 plants acre^{-1}) observed similar, nonsignificant differences from higher plant populations. This suggested that plant populations greater than 49,000 plants ha^{-1} (19,830 plants acre^{-1}) were unlikely to result in significant yield increases or losses. Differences across studies could be attributed to regional differences. Adams et al. (2019) normalized most of the studies shown in Table 1 and established that 35,000 plants ha^{-1} (14,164 plants acre^{-1}) is the minimum population density at which yield can be optimized. Although plant populations have been heavily studied in cotton farming, inconsistencies across studies suggest that additional metrics are needed to characterize cotton plant performance.

Other studies have focused on quantifying skip size and skip population instead of plant population to predict lint yield. Skip size and skip frequency are critical variables that affect yield loss and understanding the extent of these variables can provide more valuable insight than plant population. The impact of cotton skips in lint yield has been studied since the 70s (Kerby et al., 1989; Ray, 1975). Kerby et al. (1989) claimed that skips of 0.91 m (3 ft) in adjacent rows tend to decline lint yield. Furthermore, Supak and Boman (2005) suggested that stand losses as large as 30% can occur without suffering significant yield losses, but only if skips are bordered by rows with no skips. Boman and Lemon (2007) established that generally two healthy plants per foot of row in 0.76- to 1.0-m (30- to 40-in) spacing and not too many long skips will likely obtain optimum yields. These results provide useful insight on the impact of size and frequency of cotton skips in lint yield and underlined the importance of uniform spacing within rows and in adjacent rows. However, some of these studies were conducted more than 30 years ago and base their results on obsolete cultivars with lower yield potentials than modern cultivars. The definition of "long skip" size also remains unclear. In recent study, Butler (2019) reported a 45% lint yield reduction on stands of fewer than 1.5 seeds m^{-1}. Growers were advised to consider large skips as a factor that severely affects the potential yield and called for further studies to build on the effect that nonuniform stands have on yield. Opportunity exists to accurately define a significant skip size that would detrimentally affect yields.

Table 1. Reported significant and non-significant differences in lint yield between various plant populations

Study	Plant Population	Difference in Lint Yield
	---------------- plants ha^{-1} ----------------	
Zhi et al. (2016)	15,000 - 87,000	Significant
Wrather et al. (2008)	24,000 - 136,000	Significant (2 out of 4 years)
Gwathmey et al. (2011)	30,000 - 114,000	Significant
Boman and Lemon (2007)	32,500 - 65,000	Not Significant
Bednarz et al. (2005)	36,000 - 126,000	Significant
Butler (2019)	49,000 - 123,000	Not Significant
Pettigrew et al. (2013)	50,000 - 100,000	Not Significant
Craig (2010)	50,000 - 175,000	Not Significant
Pettigrew and Johnson (2005)	70,000 - 130,000	Not Significant
Main (2012)	75,000 - 150,000	Not Significant
Feng et al. (2014)	75,300 - 226,000	Not Significant

Modern unmanned aerial vehicles (UAVs) equipped with advanced sensing technologies can generate high-resolution images of entire planted areas, which can be used to make well-informed agronomic decisions. Previous studies have demonstrated that UAVs can assist in cotton yield estimations (Feng et al., 2020), manage spraying volumes of cotton defoliants (Xin et al., 2018), and detect spreading of cotton disease infections (Xavier et al., 2019). Certainly, it was worth exploring UAVs as a prospective tool for detecting cotton plants and skips in cotton farming. The study that came closest to leveraging UAVs for replanting cotton was Butler (2019), which used a combination of UAVs and geospatial analytic tools to estimate plant population and cotton uniformity. Using modern sensing technologies, ensuring that the correct metrics are applied, and updating recommendations to reflect current economic and climatic changes should provide better guidance for justifying a replanting decision.

The goal of this study was to refine recommendations established by Jost et al. (2006) using remotely sensed data while considering the cost of a replant. The authors of this paper believe Jost et al. (2006) presented the best and latest approach to informing replanting recommendation using skip size and skip frequency as a metric. The objectives of this study were to: (1) find a critical skip size that best correlated with lint yield, (2) determine the critical skipped area based on the critical skip size, and (3) evaluate the yield potential and economic benefit or drawback of replanted cotton to earlier planted cotton.

MATERIALS AND METHODS

Experimental Design. Experiments were conducted over a two-year period (2019-2020) in eastern North Carolina at the Upper Coastal Research Station in Rocky Mount; the Tidewater Research Station in Plymouth; and the Peanut Belt Research Station in Lewiston. Each site included both an early-planted (April-May) and a late-planted trial (June). Within each trial, five treatments were arranged in a randomized complete block design with four replications. Individual plots were composed of four 38-in. rows. Treatments consisted of varying ratios of transgenic DP1646 B2XF (Bayer Crop Science, St. Louis, MO) to non-transgenic cotton seed DP 493 (Bayer Crop Science, St. Louis, MO) plant population: 100, 75, 50, 25, and a 100% replant treatment. The replanted treatment plots were 100% treatment plots planted 3 to 4 wks after the initial planting and served to simulate a farmer's replant decision scenario. All trials were planted with a seeding rate of 107,491 seeds ha^{-1} (43,500 seeds $acre^{-1}$). In 2020, a 10% treatment was added to each trial. In 2019, early-planted trials were planted between 29 April and 7 May 2019 for all locations, and replanted treatments were planted between 24 and 28 May 2019 (Table 2). Late-planted trials were planted between 23 and 28 May 2019 with the replanted treatment planted between 4 and 7 June 2019. In 2020, early trials were planted between 29 April and 12 May 2020 for all locations, and the replanted treatment was planted on 26 May 2020. Late-planted trials were planted on 26 May 2020 with the replanted treatment planted between 4 and 5 June 2020. All trials were planted using a John Deere 7300 Max Emerge 4-row vacuum planter (John Deere, Moline, IL). After emergence, non-transgenic seedlings were terminated with three weekly sequential applications of 1.26 kg ae ha^{-1} of glyphosate (Roundup WeatherMAX®, Bayer Crop Science, St. Louis, MO) and 0.88 kg ai ha^{-1} of glufosinate (Liberty® 280 SL, BASF Corporation, Research Triangle Park, NC) to terminate conventional seedings and create random, nonsystematic skips.

Table 2. Planting, flying, and harvest dates (2019-2020)

Site	Trial	Planting Date	Flying Date (DAP)	Harvest Date
		2019		
Rocky Mount	Early	29 Apr.	02 July (64)	03 Oct.
	Late	24 May	02 July (39)	18 Oct.
Lewiston	Early	07 May	02 July (56)	10 Oct.
	Late	28 May	02 July (35)	23 Oct.
Plymouth	Early	07 May	11 June (35)	15 Oct.
	Late	23 May	11 June (19)	24 Oct.
		2020		
Rocky Mount	Early	29 Apr.	18 June (49)	15 Oct.
	Late	26 May	18 June (25)	28 Oct.
Lewiston	Early	29 Apr.	26 June (57)	14 Oct.
	Late	26 May	26 June (31)	27 Oct.
Plymouth	Early	12 May	03 July (46)	19 Oct.
	Late	26 May	03 July (38)	21 Oct.

A Zenmuse X5 RGB sensor (DJI, Shenzen, China) mounted to a DJI Matrice 600 Pro (DJI, Shenzen, China) was used to collect images over each site after all non-transgenic plants were terminated. Flights were carried out at an altitude of 53 m (175 ft) above ground level (AGL) during 2019 and 30 m (100 ft) AGL during 2020. The decision to decrease the altitude improved the timing of detection after planting and did not compromise data integrity. Two image processing programs were used to generate plant count files: PrecisionHawk Ag Analytics (Precision Hawk, Raleigh, NC) and Solvi (Solvi, Gothenburg, Sweden). PrecisionHawk Ag Analytics was used during 2019, and Solvi was used during 2020. Both software programs use the same processing algorithm to generate RGB orthomosaics and plant counts, so the switch did not affect the results of this study. Only the inner two rows of each 4-row plot were analyzed. The first plant from each plot was selected as the reference plant during 2019. Similarly, each row ended with the last plant within the center two rows. Conversely, dummy plants were placed at the start and end of each row during 2020 to account for skips that occurred in the plot edges (Fig. 1). Distances between the reference plant and all other plants were measured using the Distance Matrix tool in QGIS 3.8.0 (QGIS Development Team, https://qgis.org/en/site/) for all 2019 trials and the Near tool in ArcGIS Pro (Esri, Inc., Redlands, CA) for all 2020 trials.

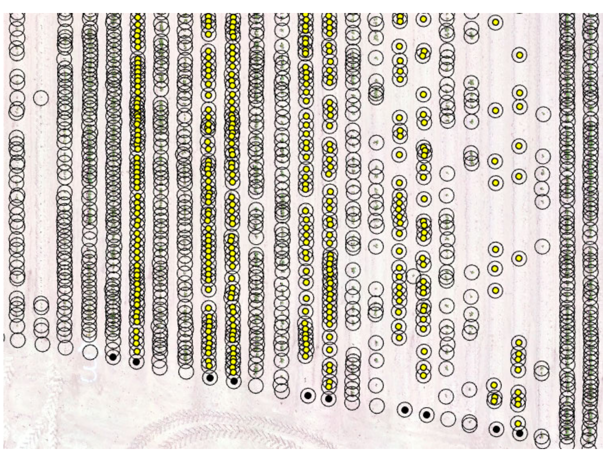

Figure 1. Reference (black) and target (yellow) plant detections in Lewiston Early 2020.

Next, the distances between subsequent plants were calculated via a coded script written in RStudio (RStudio, Boston, MA). The code also categorized each of the measured distances as size skips that were greater than or equal to 0.61, 0.76, 0.91, 1.06, or 1.2 m (2.0, 2.5, 3.0, 3.5, or 4.0 ft), respectively. For example, all measurements that were greater than or equal to 0.61 m (2 ft) fell under the 0.61 m (2.0 ft) category, and all measurements greater than or equal to 1.06 m (3.5 ft) fell under the 0.61, 0.76, 0.91, and 1.06 m (2.0, 2.5, 3.0, and 3.5 ft) category. Therefore, the smaller skip size categories contained more data than the larger skip size categories. The skipped area percentage within each plot was calculated using equation 1.

$$Skipped\ Area\ Percentage = \left(\frac{\sum_{i=1}^{n} S_i}{2L}\right) \times 100 \quad (1)$$

Where, S = skips greater than or equal to 0.61, 0.76, 0.91, 1.06, or 1.2 m (2.0, 2.5, 3.0, 3.5, or 4.0 ft); L = length of the plot; i = index counter for skips greater than or equal to 0.61, 0.76, 0.91, 1.06, or 1.2 m (2.0, 2.5, 3.0, or 4.0 ft); and n = total number of skips in the plot.

Statistical Methods. After harvesting with a John Deere 9960 4-row spindle-type cotton picker (John Deere Moline, IL), lint yield was recorded for each plot with a boll buggy equipped with a three-load cell Weigh-Tronix scale system (Avery Weigh-Tronix, Fairmont, MN). Subsamples of seed cotton were sent to the University of Tennessee Microgin for ginning and subsequent High Volume Instrumentation (HVI) analysis of fiber quality. Harvest dates are shown in Table 2. A multiple linear regression model that included site, trial, and treatment as categorical variables was used to model the response of lint yield during each year. An analysis of variance (ANOVA) was conducted in R to test the differences between all group means. Subsequently, all treatments within all trials were subjected to Tukey's Honest Significant Difference (HSD) and means were separated at $\alpha < 0.05$. A simple linear regression was used to model the effect of skipped area on lint yield for each skip size category. Pearson correlation coefficient values were obtained using the ggpairs() function in the GGally R package (Schloerke et al., 2021) to indicate the critical skip size that best predicted lint yield.

Based on the critical skip size, the total skipped area was calculated as a percentage of the entire planted area for each trial. Then, each plot's lint yield was divided by the replant lint yield in the corresponding replication to estimate a lint yield to replanted lint yield ratio. The replant lint yield accounted for the economic cost that presumes a replant. So, the estimated cost of replanting, \$86 ha^{-1} (\$35 acre^{-1}), was divided by the value of lint as of 2020 in the USDA-AMS report (USDA-AMS, 2021), \$1.60 kg^{-1} (\$0.73 lbs^{-1}) to estimate a yield penalty of 54 kg ha^{-1} (48 lbs acre^{-1}). Then, this value was subtracted from the replant lint yield. The lint-yield-to-replant-lint-yield ratio was regressed to the skipped area percentage from each trial. Last, the fitted skipped area percentage that matched a 1:1 lint-yield-to-replanted-lint-yield ratio was calculated from each trial. This value represented the threshold that would justify a replant in each trial. Plots from all trials that yielded higher and lower than a ratio value of 1.0 were also identified. Finally, accumulated precipitation and DD60 was recorded at each research station throughout both growing seasons. These parameters helped this study explain some of the events that occurred post-emergence and throughout each growing season.

RESULTS AND DISCUSSION

Blending transgenic and non-transgenic seeds at known ratios was effective at simulating nonsystematic skips of various sizes. Cotton plants were successfully detected using UAV-based imagery. Flights conducted at 30 m (100 ft) AGL during 2020 provided better image resolution than flights at 53 m (175 ft) AGL during 2019, and hence allowed for plants to be detected earlier. Some trials had to be revisited on later dates. Successful plant detections occurred when plants had between four to six true leaves. Table 2 shows the flying date at which the plants were successfully detected and the days after planting (DAP) when they occurred. The earliest plant detections occurred in Plymouth Late at 19 DAP. Other trials required more than 30 DAP to collect images from which plant detections could be made. Detections this late might cause producers to miss optimal planting date windows or surpass crop insurance deadlines. Although 19 DAP is a relatively long time, there is still a chance to assess the replanting decision and achieve optimal yields if the original planting occurred at an early date.

Means for lint yield of each treatment are illustrated in Table 3 and Table 4. There were 10 trials over both years that exhibited no significant differences among yields for the 100, 75, and 50% stand treatments, suggesting that a stand loss as large as 50% in any given planted area would most likely not justify replanting if initial rate was 107,600 sd ha^{-1} (43,560 sd acre^{-1}). These results were similar to those described by Pettigrew et al. (2013), where no significant differences were observed between populations of 10,000 plants ha^{-1} (40,469 plants acre^{-1}) (100% stand) and 50,000 plants ha^{-1} (20,234 plants acre^{-1}) (50% stand). The 25% stand treatment yielded poorer than the 100 and 75% stand treatments in six trials and yielded poorer than 50% stand treatment in four trials. As expected, the 10% stand treatment in the 2020 trials yielded poorly compared to the treatments with higher plant populations. This suggested that a planted area with an extreme 90% stand loss would likely require a replant.

Table 3. Within treatment yield ANOVA test and Tukey's HSD. Alpha value = 0.05. Study year: 2019

Treatment	Lint Yield (kg ha^{-1})					
	Lewiston Early	Plymouth Early	Rocky Mount Early	Lewiston Late	Plymouth Late	Rocky Mount Late
100%	1,757 a[z]	1,062 a	1,213 a	1,503 a	1,216 a	1,208 a
75%	1,814 a	1,056 a	1,059 b	1,505 a	1,145 a	1,127 a
50%	1,723 a	1,015 ab	977 bc	1,475 a	1,111 a	1,137 a
25%	1,537 b	879 b	1,003 bc	1,267 b	955 b	960 b
Replant	1,465 b	1,083 a	923 c	1,322 b	710 c	982 b
LSD	138	158	130	122	146	65
SE	46	52	43	40	48	22

[z] Means with a column followed by the same letter are not different at $p \leq 0.05$.

Table 4. Within treatment yield ANOVA test and Tukey's HSD. Alpha value = 0.05. Study year: 2020

Treatment	Lint Yield (kg ha^{-1})					
	Lewiston Early	Plymouth Early	Rocky Mount Early	Lewiston Late	Plymouth Late	Rocky Mount Late
100%	875 a[z]	629 a	706 b	1,069 a	589 a	854 a
75%	861 a	598 ab	687 b	988 ab	592 a	846 a
50%	826 ab	536 ab	661 b	985 ab	561 a	875 a
25%	745 b	389 b	538 b	902 ab	495 a	775 a
10%	443 c	200 c	240 c	578 d	289 b	557 b
Replant	906 a	674 a	942 a	748 c	554 a	799 a
LSD	89	166	213	140	130	142
SE	30	56	72	47	44	48

[z] Means with a column followed by the same letter are not different at $p \leq 0.0$

The replanted treatment yielded virtually equal or lower than the 25% treatment in most early and late trials during 2019, suggesting that late-planted or replanted cotton might not always result in optimal yields. These results aligned with recommendations established by Wrather et al. (2008) that discouraged replanting after mid-May if populations from early planting were greater than 16,990 plants ha^{-1} (6,876 plants acre^{-1}). The 2020 replant treatment plots yielded virtually equal or higher than the 100% treatment plots in five out of six trials (Fig. 2, Table 4). Inconsistencies with replant treatments across 2019 and 2020 trials suggested that it is best to avoid replanting unless more than 75% of the planted area has been lost, especially if replanting is to occur during the month of June. Butler (2019) also observed significant yield reductions after planting during the month of June.

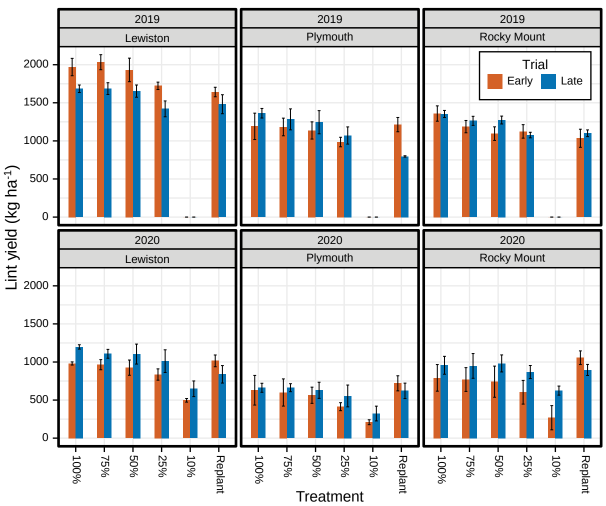

Figure 2. Lint yield bar chart across treatments, trials, and locations (2019-2020).

Differences between early- and late-trial yields of stand loss treatments and their respective replanted treatments can be attributed to the evident discrepancies in DD60s and precipitation observed throughout the two-year study (Figs. 3 and 4). Warmer temperatures and wetter soils during the late month of April and throughout the month of May 2019 allowed for uniform and rapid emergence. The optimal growing conditions continued throughout late planting and produced exceptional stands and lint yields, even at the 25% treatment level. Results clearly illustrated statistical similarities within the trial levels (Table 5) during 2019. Conversely, cooler temperatures and wetter soils detrimentally affected germination in early-planted stands and lint yield in 2020. Temperatures improved by the time the late-planted trials were planted and contributed to the production of superior stands in the later planted trials, as compared to the earlier planted trials during 2020. Clear statistical evidence showing the difference between trials is presented in Table 6. Results in 2020 were consistent with Collins and Edmisten (2019), which supported late planting when conditions were favorable. The clear distinction between both experimental years indicated that planting yields were highly dependent on the weather conditions. Results further underline the importance of customizing recommendations based on local weather patterns.

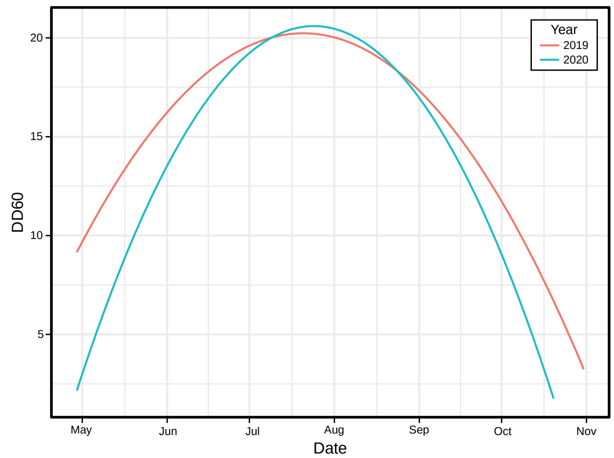

Figure 3. Fitted DD60 during the typical NC cotton growing period.

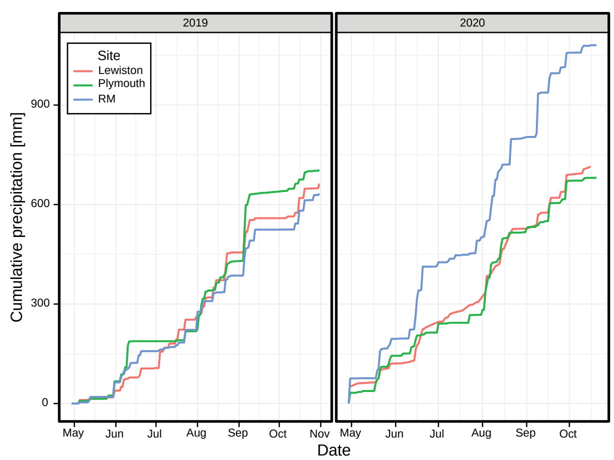

Figure 4. Cumulative precipitation during the typical growing period for NC cotton (2019-2020).

Table 5. Between-subject ANOVA test. Study year: 2019

	Sum Sq	df	F value	Pr(>F)
Site	1644611	2	70.0	2.90E-10
Trial	29698	1	2.5	0.12611
Treatment	291652	4	6.2	0.00168
Residuals	258446	22	NA	NA

Table 6. Between-subject ANOVA test. Study year: 2020

	Sum Sq	df	F value	Pr(>F)
Site	611126	2	42.8	4.26E-09
Trial	66885	1	9.4	0.00496
Treatment	1542069	5	43.2	4.77E-12
Residuals	192851	27	NA	NA

Correlation values between the skipped area and lint yield varied between 0.46 and 0.78 across all skip sizes and between both years. In 2019, each of the skip sizes had correlation values that spanned from 0.46 to 0.56 with lint yield (Table 7). Linear variations in lint yield were best explained by skips of 0.61 m (2.0 ft) or greater with a correlation value of 0.555. Correlation values decreased slightly as the skip size increased. This seems reasonable because the smaller the skip size, the larger the resolution of the skipped area will be. Nevertheless, that was not the case the following year. Lint yield in 2020 was best explained by 1.2-m (4.0-ft) skips with a correlation of 0.778, and correlation values decreased slightly as skip size decreased. One possible explanation to this anomaly is that there were not enough larger-sized skips (e.g., 0.91-m and 1.2-m skip sizes) during 2019 to make an accurate prediction of lint yield with larger-sized skips. Most large skips were observed in the 25% treatment, and few were found in the higher stand treatments. This can be evidenced with the clustering of points in the left-most portion of Fig. 5. Because a 10% treatment was added during 2020, it is plausible that the better linear agreement observed in 2020 was due to the increased number of larger skips detected.

Table 7. Correlation (R^2) values between lint yield and skip size

Year	Skip Size				
	0.61 m (2.0 ft)	0.76 m (2.5 ft)	0.91 m (3.0 ft)	1.06 m (3.5 ft)	1.2 m (4.0 ft)
2019	0.56	0.55	0.52	0.49	0.46
2020	0.73	0.75	0.76	0.77	0.78

Combined results suggest that no skip size is critical for measuring skipped area. It is plausible that too many smaller skips (e.g., 0.61-m skips) can have the same detrimental effect in lint yield potential as fewer, larger skips. The lack of agreement in correlation trends between both study years motivated the decision to choose 0.91-m (3.0-ft) skip level as the explanatory variable in Fig. 5 and Fig. 6 because it has been the most recommended measure in the past.

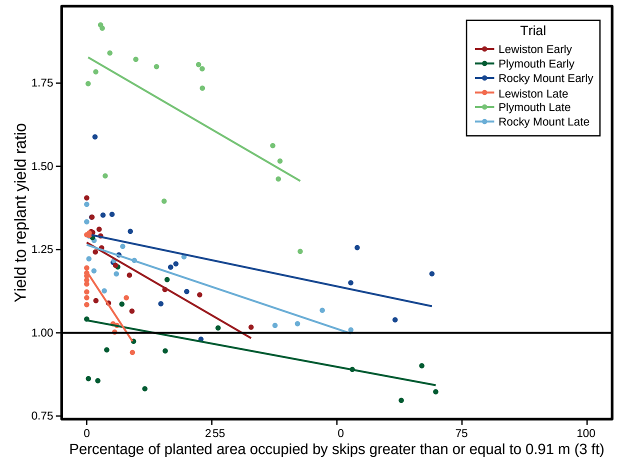

Figure 5. Relationship between the yield to replant yield ratio and the percentage of planted area occupied by skips greater than or equal to 0.91 m (3 ft). Study year: 2019.

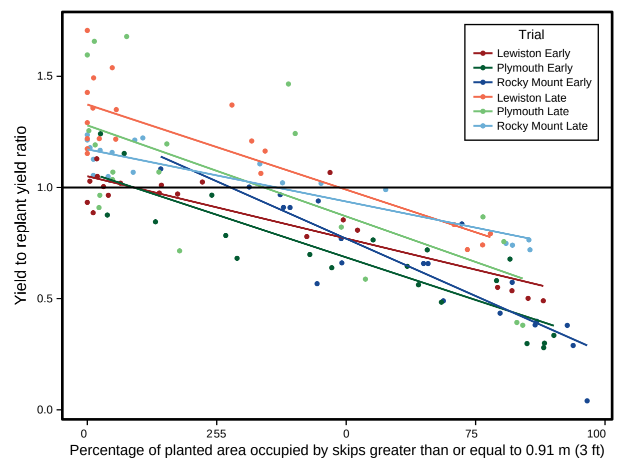

Figure 6. Relationship between the ratio of yield to replant yield and the percentage of planted area occupied by skips greater than or equal to 0.91 m (3 ft). Study year: 2020.

As alluded earlier, replanting was generally not recommended during 2019 trials by virtue of the optimal conditions that were present during early and late planting, which resulted in higher yields across all treatments compared to replanted treatment. Most plots within each trial yielded more than the 1:1 yield-to-replant-yield ratio (Fig. 5). The 2019 late-planted trial at Plymouth had the largest yield-to-replant-yield ratio due to the poor performance in the late replanted yield. The lack of plots that yielded below the 1:1 ratio and the clustering of points in the left-portion of Fig. 5 hindered the predictions of skipped area percentage thresholds. To the latter point, it is plausible that the observed clustering could have leveraged the regression. Still, predictions were carried out to provide estimates for replanting thresholds for each trial.

Most of the threshold values were estimated to be in the 40 to 50% range for 0.91-m (3.0-ft) skips in 2019 (Table 8). This is consistent with Jost et al. (2006), who recommended a replant if 50% of the planted area was occupied by skips greater than or equal to 0.91 m (3.0 ft). Considering that the former study was conducted more than 15 years ago using manual measurements, these percentages are surprisingly similar. However, results from this study suggest that this recommendation should remain true for seasons where warm temperatures prevail throughout the months of April and May; it is plausible that Jost et al. (2006) also observed similar conditions throughout the experimental period. The conservative nature of the recommendation frames the replant as an unlikely scenario. Unless an external factor occurs, such as poor-quality seed, replanting will most likely not be necessary under optimal weather conditions. The decision gets more complicated because long-term weather is difficult to predict and usually unknown at the time of planting.

Table 8. Percentage of planted area that would justify a replant based on 2019 experimental results

Site	Trial	Skip Size				
		0.61 m (2.0 ft)	0.76 m (2.5 ft)	0.91 m (3.0 ft)	1.06 m (3.5 ft)	1.2 m (4.0 ft)
Rocky Mount	Early	60	48	40	33	26
	Late	64	52	42	33	27
Plymouth	Early	32	25	20	16	13
	Late	78	64	50	38	30
Lewiston	Early	41	27	19	15	12
	Late	17	9	5	3	2

A larger number of plots yielded below the 1:1 yield-to-replant-yield ratio in 2020 (Fig. 6). This suggests that a decision to replant would have probably resulted in increased yields for the plots that yielded below this threshold. The addition of the 10% stand treatment in 2020 helped explain part of the variation that occurred at higher skipped area percentages, eliminated any concerns regarding clustering, and contributed to increasing the linear correlation from 0.50 to 0.70. Most skipped area percentages varied between 30 to 40% (Table 9), suggesting that the replanting threshold should be established within that range. This threshold is less conservative than the recommended threshold by Jost et al. (2006), and because weather patterns observed during 2020 were more consistent with years prior to 2019, 30 to 40% appears to be the true replanting threshold that is applicable for NC cotton farming. Nevertheless, variations in atypical weather conditions have shown to skew the threshold over and under the 30 to 40% range, and farmers must remain vigilant to volatile climatic changes.

Table 9. Percentage of planted area that would justify a replant based on 2020 experimental results

Site	Trial	Skip Size				
		0.61 m (2.0 ft)	0.76 m (2.5 ft)	0.91 m (3.0 ft)	1.06 m (3.5 ft)	1.2 m (4.0 ft)
Rocky Mount	Early	51	42	34	28	22
	Late	45	39	35	32	28
Plymouth	Early	33	24	18	15	12
	Late	43	36	31	27	24
Lewiston	Early	27	19	14	10	8
	Late	53	47	41	37	33

CONCLUSIONS

Replanting decisions have become more important in recent years now that the costs associated with replanting cotton are considerable. In 2020, the cost of a replanting was the equivalent of losing an estimated 56 kg ha^{-1} (50 lbs $acre^{-1}$) lint or more, due to poor stands. Given the tedious and cumbersome nature of manual measurements of stand loss, many growers make replanting decisions based on visual assessments of stand loss. Although previous studies provide a good baseline to determine when a replant might be justified, concerns remain regarding the conservative nature of those recommendations. The rise of remote sensing technologies in agriculture allowed for quicker and precise plant and skip detections to be conducted. This study explored the validity from past recommendations and improved their accuracy and precision using UAV technology. More specifically, the focus of this study was to refine the critical skip size and the critical skipped area that would justify replanting. It was concluded that replanting is more likely justified when 30 to 40% of planted area is occupied with 0.91-m (3.0-ft) skips or greater for NC weather.

The replanting decision continues to be an enigma due to the numerous environmental, agronomic, and economic factors involved. Further complicating a replant decision is that there is not a guarantee that a replant will emerge satisfactorily.

Experienced growers will attempt to work with a suboptimal stand rather than to undergo a replant. However, growers that use UAVs to count plants could benefit from guidelines that explain how to measure skips and to assess replanting needs. Future research should focus on drafting these guidelines taking into consideration the effect of evolving climatic and economic patterns.

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REFERENCES

Adams, C., S. Thapa, and E. Kimura. 2019. Determination of a plant population density threshold for optimizing cotton lint yield: A synthesis. Field Crops Res. 230:11–16. https://doi.org/10.1016/j.fcr.2018.10.005

Bauer, P.J., and J.M. Bradow. 1996. Cotton genotype response to early-season cold temperatures. Crop Sci. 36(6):1602–1606. https://doi.org/10.2135/cropsci1996.0011183X003600060032x

Bednarz, C.W., W.D. Shurley, W.S. Anthony, and R.L. Nichols. 2005. Yield, quality, and profitability of cotton produced at varying plant densities. Agron. J. 97(1):235–240. https://doi.org/10.2134/agronj2005.0235a

Boman, R., and R. Lemon. 2007. Making replant decisions in cotton. Publ. SCS-2007–08. Texas A&M Univ. Dept. of Soil and Crop Sci. Available online at https://amarillo.tamu.edu/files/2017/06/Cotton-Replant-Decisions-07.pdf (verified 22 Aug. 2022).

Butler, S.A. 2019. Making the replant decision: utilization of an aerial platform to guide replant decisions in Tennessee cotton. Ph.D. diss., Univ. Tennessee, Knoxville. Available online at https://trace.tennessee.edu/utk_graddiss/5959 (verified 22 Aug. 2022).

Collins, G., and K. Edmisten. 2019. Late planting & evaluating hail damage. NC State Ext. Available online at http://go.ncsu.edu/readext?605529 (verified 22 Aug. 2022).

Craig, C. 2010. Making cotton replant decisions. Univ. Tennessee Agric. Ext. Ser. Publ. W073. Available online at https://trace.tennessee.edu/utk_agexcrop/86/ (verified 22 Aug. 2022).

Dodds, D. 2013. Cotton replant costs. Mississippi Crop Situation, Mississippi State Univ. Ext. Blog. Available online at https://www.mississippi-crops.com/2013/05/11/cotton-replant-costs/ (verified 22 Aug 2022).

Feng, A., J. Zhou, E. Vories, and K.A. Sudduth. 2020. Evaluation of cotton emergence using UAV-based imagery and deep learning. Comput. Electron. Agric. 177:105711. https://doi.org/10.1016/j.compag.2020.105711

Feng, L., G. Mathis, G. Ritchie, Y. Han, Y. Li, G. Wang, X. Zhi, and C.W. Bednarz. 2014. Optimizing irrigation and plant density for improved cotton yield and fiber quality. Agron. J. 106(4):1111–1118. https://doi.org/10.2134/agronj13.0503

Gwathmey, C.O., L.E. Steckel, J.A. Larson, and D.F. Mooney. 2011. Lower limits of cotton seeding rates in alternative row widths and patterns. Agron. J. 103(3)584–592. https://doi.org/10.2134/agronj2010.0333

Jost, P.H., A.M. Stewart, and J. Siebert. 2006. Skippy stands and replanting: development of a decision aid. p. 1856–1858. *In* Proc. Beltwide Cotton Conf., San Antonio, TX. 3-6 Jan. 2006. Natl. Cotton Counc. Am., Memphis, TN.

Kerby, T., S. Johnson, and K. Hake. 1989. When to replant. California Cotton Rev. 9. Univ. Calif. Coop. Ext. Available online at https://cottoninfo.ucdavis.edu/files/133153.pdf (verified 22 Aug. 2022).

Kittock, D.L., B.B. Taylor, and W.C. Hofmann. 1987. Partitioning yield reduction from early cotton planting. Crop Sci. 27(5):1011–1015. https://doi.org/10.2135/cropsci1987.0011183x002700050038x

Main, C.L. 2012. Cotton growth and development. Univ. Tennessee Ext. Publ. W287. Available online at https://trace.tennessee.edu/utk_agexcrop/155/ (verified 22 Aug. 2022).

McQuigg, J.D., O.H. Calvert, and W.L. Decker. 1965. Using weather information to cut the cost of getting a good stand of cotton in southeast Missouri. Univ. Missouri Agric. Exp. Sta. Publ. 835. Available online at https://mospace.umsystem.edu/xmlui/bitstream/handle/10355/55116/AESbulletin.pdf?sequence=1&isAllowed=y (verified 22 Aug. 2022).

Pettigrew, W.T., and J.T. Johnson. 2005. Effects of different seeding rates and plant growth regulators on early-planted cotton. J. Cotton Sci. 9(4):189–198.

Pettigrew, W.T. and W.R. Meredith Jr. 2009. Seed quality and planting date effects on cotton lint yield, yield components, and fiber quality. J. Cotton Sci. 13(2):37–47.

Pettigrew, W.T., W.R. Meredith Jr., and L. Zeng. 2013. Response of obsolete and modern cotton genotypes to varying plant densities. J. Cotton Sci. 17(4):253–262.

Ray, L.L. 1975. What is a cotton stand? p. 25–27. *In* Proc. Western Cotton Prod. Conf.

Schloerke, B., D. Cook, J. Larmarange, F. Briatte, M. Marbach, E. Thoen, A. Elberg, O. Toomet, J. Crowley, H. Hofmann, and H. Wickham. 2021. GGally: extension to 'ggplot2'. Available online at https://cran.r-project.org/package=GGally (verified 22 Aug. 2022).

Supak, J., and R. Boman. 2005. Making replant decisions. Texas A&M Univ. Agric. Ext. Ser. Available online at http://publications.tamu.edu/COTTON/PUB_cotton_Making%20Replant%20Decisions%20in%20Cotton.pdf (verified 22 Aug. 2022).

United States Department of Agriculture, Agricultural Marketing Service [USDA-AMS]. 2021. Cotton Price Statistics 2020-2021. Available online at https://www.ams.usda.gov/mnreports/cnaacps.pdf (verified 22 Aug. 2022).

Whitaker, J., G. Collins, G. Harris, and S. Culpepper. 2013. Cotton with wet feet–management considerations for wet and excessively wet cotton in 2013. Georgia Cotton News. Univ. Georgia Coop. Ext. Available online at http://www.ugacotton.com/2013/07/cotton-with-wet-feet-managment-considerations-for-wet-and-excessively-wet-cotton-in-2013/ (verified 22 Aug. 2022).

Wrather, J.A., B.J. Phipps, W.E. Stevens, A.S. Phillips, and E.D. Vories. 2008. Cotton planting date and plant population effects on yield and fiber quality in the Mississippi Delta. J. Cotton Sci. 12(1):1–7.

Xavier, T.W.F., R.N.V. Souto, T. Statella, R. Galbieri, E.S. Santos, G.S. Suli, and P. Zeilhofer. 2019. Identification of ramularia leaf blight cotton disease infection levels by multispectral, multiscale UAV imagery. Drones. 3(2):33. https://doi.org/10.3390/drones3020033

Xin, F., J. Zhao, Y. Zhou, G. Wang, X. Han, W. Fu, J. Deng, and Y. Lan. 2018. Effects of dosage and spraying volume on cotton defoliants efficacy: a case study based on application of unmanned aerial vehicles. Agron. 8(6):85. https://doi.org/10.3390/agronomy8060085

Zhi, X., Y. Han, Y. Li, G. Wang, W. Du, X. Li, S. Mao, and L. Feng. 2016. Effects of plant density on cotton yield components and quality. J. Integrative Agric. 15(7):1469–1479. https://doi.org/10.1016/S2095-3119(15)61174-1