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ENGINEERING & GINNING

Cotton Ginning Rate Prediction Model Development for Commercial Gins: Impact of Variety, Quality, and Moisture Content

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ABSTRACT

One of the most important factors impacting the profitability of a cotton ginning operation is the number of bales produced per hour, as higher ginning rates typically reduce energy and labor costs on a per bale basis. Data from eight commercial gins were used to evaluate the impact of incoming seed cotton attributes such as fiber quality measurements, moisture content, and variety on gin throughput. After normalizing the data by gin, time of year, and bale weight, models were developed to quantify the impact of fiber quality and seed cotton variety characteristics on ginning rate. Post-ginning lint quality attributes, such as extraneous matter, negatively influenced ginning rate. Higher micronaire values and reflectance corresponded to faster ginning rates, whereas increases in yellowness resulted in a decreased ginning rate. The interaction of reflectance and micronaire negatively affected ginning rate. Seed cotton variety characteristics included lint percentage and bract trichomes, which negatively influenced ginning rate, whereas fiber density positively influenced it. The study also indicated that ginning rate abruptly drops when seed cotton moisture content reaches an upper threshold. Additionally, the initial and final weeks of ginning have a slower ginning rate than the middle part of the ginning season. A ginning rate calculator was developed using models to predict ginning rate and justify variable ginning rates based on incoming seed cotton variety characteristics and lint properties.

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Agricultural and gin machinery are capable of capturing significant amounts of data during operation. The latest cotton harvester from John Deere can provide data such as module weight, moisture, and GPS coordinates for where a module was both wrapped and dropped (Hardin et al., 2022; Wanjura et al., 2020). Figure 1 shows data flow during cotton harvesting and ginning in the U.S. The blue boxes illustrate where cotton data flow has been automated for more than 25 years. The harvester's data is associated with a radio frequency identification (RFID) tag for each seed cotton module produced (Hardin et al., 2022). RFID tags also can be associated with ownership information to track the cotton from the field to the gin. Before a bale of lint leaves the bale press in a cotton gin, a permanent bale identifier (PBI) is assigned to the bale, and a sample is taken. The lint sample taken from each bale with the PBI identifier is sent to the U.S. Department of Agriculture-Agricultural Marketing Service (USDA AMS) to measure the fiber quality properties. With the RFID tag, it is easy to link the data associated with a module such as harvest date, seed cotton moisture content, and area of the field the cotton came from. Additional data collected at the gin during processing such as moisture content of the seed cotton or fiber during processing, energy use, and motor loads also can be associated with the module and bales as they are being processed. Given the various analytical tools now available, the overall objective of this study was to determine if these data could be used to optimize a gin's production rate such that the rate was as fast as possible without excessive fiber damage or risk of a work stoppage.

Potential Factors Impacting Ginning and Spinning Systems. The performance of both ginning

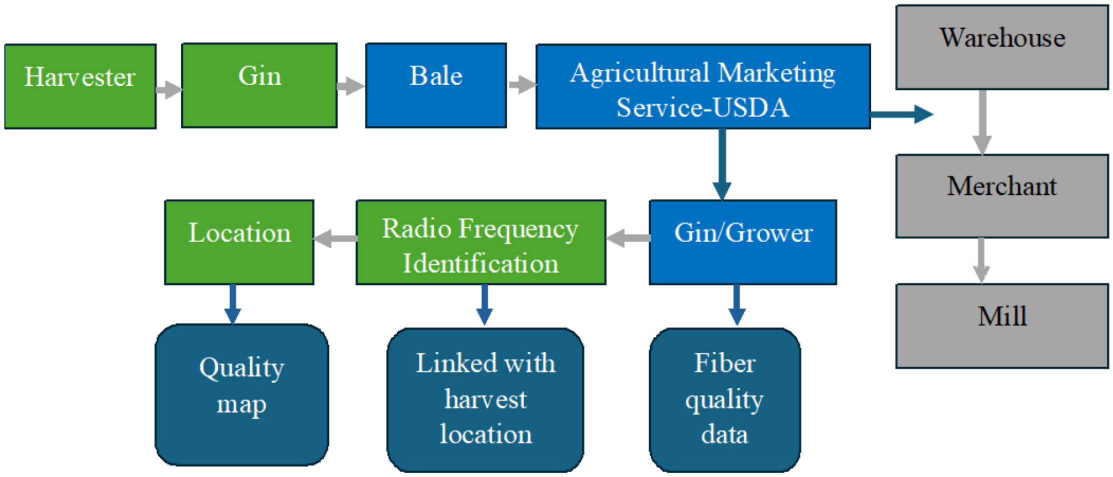

Figure 1. Data flow during cotton harvesting and ginning in the U.S. (Hardin IV et al., 2022).

and spinning systems is dependent on incoming seed cotton variety characteristics, lint properties, type of gin used, and environmental factors. Some of these quality attributes critical for both ginning and spinning systems performance are trash content, fiber length, color, maturity, fiber strength, and contamination. According to Acharya et al. (2024), the ginning method used greatly impacts the ginning rate (bales per hour [bph]), cost, and quality of the lint. Even though maximizing the ginning rate and reducing the ginning cost is vital, it should not compromise the lint quality produced. Table 1 lists various factors that impact the ginning and spinning systems.

Objectives of the Current Research. The U.S. cotton industry has a long history of benefiting from the fiber quality data the USDA-AMS classing office provides on every bale of cotton produced. Currently, agricultural and ginning machinery automatically collects a large amount of harvesting and ginning data and adding automated data logging of additional parameters such as ginning rate (bph) and energy use is possible with minimal costs and modification to the gin. With the growing data sources, the National Cotton Ginners Association Technology Committee launched an effort to evaluate opportunities for ginners and producers to gain more value from the data currently collected. These priorities were translated to a multi-year Cotton Incorporated-led cotton gin data project with contributions from multiple U.S. Department of Agriculture-Agricultural Research Service (USDA ARS) gin labs, SAS Institute, National Cotton Ginners Associations, universities, and ginners to understand various factors impacting the ginning rate (bph). The hypothesis of this study is that various factors such as seed cotton variety characteristics (e.g., lint percent [LP], bract trichomes [Btri], fiber density [Fden] and fibers per seed [FPS]), seed cotton moisture content, and lint quality properties such as fiber strength, length, and maturity, and moisture and trash content will impact ginning rate (bph).

The present research analyzed saw-ginned Upland cotton data from commercial cotton gins in the U.S. The research focused on several aspects, including the number of bales processed by each gin, which depends on the specific variety of incoming seed cotton and lint properties. Additionally, the study examined other relevant factors, such as week of ginning and moisture content of incoming seed cotton impact on ginning rate. By considering these elements, the research aims to gain a better understanding of the commercial ginning process and its influencing factors. The specific objectives of this research are: (1) identify factors the gin can control that affect the ginning rate (bph) and stoppages or downtime; (2) analyze and model the ginning rate (bph) using gin process data collected from commercial gins and understand the impact of gin-available data, seed cotton variety characteristics, lint quality, and other factors on the ginning rate; and (3) develop prediction models for ginning rate (bph) with respect to lint properties and incoming cotton variety characteristics.

MATERIALS AND METHODS

In the project's first year, a pilot study was conducted to analyze data from two gins over five

Table 1: Factors impacting ginning or spinning systems

Factors	Impact on the ginning or spinning rate	Source
	Lint quality	
Fiber length	Longer fibers generally lead to higher ginning or spinning rates because longer fibers have a higher surface area where they can be fed and taken up faster in the spinning system.	Wilson (2011); Chattopadhyay et al. (2023); Song et al. (2017)
Fiber strength	Stronger fibers can withstand damage during spinning, allowing faster processing. Lower leaf, reduced length, and strength increase neps formation resulting in poor mill performance.	Valco (n.d.); Hardin IV et al. (2018)
Fiber maturity	Immature fiber (indicated by lower micronaire) is more sensitive to mechanical handling, being more prone to fiber breakage and nep formation. The higher immature fiber in the seed cotton can result in slowing the ginning rate, as the gins have to work harder to separate immature fiber from seed, which can result in fiber breakage, increase short fiber content, fiber entanglements (neps), resulting in more non-lint material in the final product. Higher immature fibers can also reduce ginning or spinning efficiencies as the settings on the machine have to be adjusted to handle immature fibers, such as lowering gin speed, feed rate, or modifying the airflow.	Krifa (2006); Mangialardi et al. (1987); Hebert et al. (1986); Hardin IV et al. (2018); Kim et al. (2021); Ayele et al. (2017)
Seed cotton or lint moisture content	Maintaining proper moisture level is crucial for efficient ginning or spinning. Dry seed cotton can increase fiber breakage and lower ginning rates, whereas excessive moisture can lead to clogging and reduced efficiency.	Funk and Hardin IV (2017); Boykin (2005)
Trash content	High levels of impurities in seed cotton can reduce ginning yield.	Kouakou et al. (2024)
Seed cotton variety	Seed cotton grade and variety impacts ginning efficiency. For example, selecting cotton varieties with favorable characteristics such as lint percentage, fiber density, and bract trichomes can greatly enhance ginning performance.	Beheary et al. (2019)
	Gin machine type	
Ginning system	Saw gins have a higher ginning rate compared to roller or reciprocating gins.	Acharya et al. (2024)
Precleaning and gin machine maintenance	The age of rollers or saws used in the ginning machine can significantly affect ginning efficiency. Regular maintenance of precleaning and ginning systems is essential for optimal performance.	Funk and Hardin IV (2019).
Feed rate	A steady flow of seed cotton is ideal for optimal ginning. Feeding too much cotton at once can cause fiber entanglement and reduce the ginning rate.	Mangialardi et al. (1988); Hardin IV et al. (2018)
	Other factors	
Environmental factors	Extreme temperatures and high humidity can affect the ginning process by causing slowdowns.	M.B. McKee Co. (2024)

seasons to see if predicting ginning rate (bph) and gin slowdowns was feasible. The data provided by the ginners for the present data analysis project are for saw-ginned Upland cotton. A total of 120,000 bales were available for the analysis, and variety was known for 50,000 bales. Table 2 provides a summary of the data type collected from different gins. These data include the number of bales processed, seed cotton variety, and USDA-AMS classing office data. The data related to type and model of gin stands, number of gin stands used, and number of modules each gin stand has processed are not part of the data collected as the study was focused on factors influencing the relative ginning rate for a given gin, not to predict an absolute ginning rate based on equipment configurations. Cotton variety characteristics data were taken from the work done by the University of Arkansas (Bourland et al., 2022).

Table 2. Overview of data collected from commercial gins

Number of gins	Data types used for analysis and modeling
8	Cotton variety
	Bale weight[z] (lbs; kg)
	USDA Agricultural Marketing Service Classing Office data
	Ginning rate (bales per hour; bph)
	Seed cotton and lint moisture content (%, w.b.)
	Date and time bale was ginned

[z]Average bale weight of ginning season

Based on first-year observations, in the second year, more data were analyzed by incorporating more gins to determine (1) if relationships found from the previous year's study were maintained with a more diverse set of cotton gins; (2) for gins with added data, determine what added measures brought the most value and should be considered by other cotton gins; (3) better understand the relationship between variety characteristics and gin performance; and (4) determine the feasibility of a model to predict ginning rate that could both be used for process control and to help set prescriptive ginning charges.

This project tested various analytical and modeling approaches to analyze the commercial gins data and understand the impact of factors such as quality, variety, and moisture on the ginning rate. Data aggregated across seven U.S. Southeast, Midsouth, and Gulf Coast gins represented 12 crop years with more than 500,000 bales. Although eight gins shared the data, only data from seven gins were used because one of the gins did not have data on ginning rate (bph). The data collected from the eighth gin for lint quality were used in the analysis. Ginners provided the processing data in Excel sheet format to Cotton Incorporated, which was further anonymized and shared with SAS Institute and USDA-ARS scientists. These data were further used to develop models for bph given variety and lint properties, considering gin metadata such as gin ID and week of the year (ginweek). Some potential explanatory variables, such as seed cotton variety name, harvesting method, and time and location of the harvesting, were not consistently recorded among gins or across years within a gin. Table 3 lists typical seed cotton varieties processed by the eight commercial gins included in the gin datasets for the 2021 crop season.

The commercial gin data collected were used to develop models to predict ginning rate (bph) given variety and fiber quality properties, considering gin metadata such as gin ID (gin number indicator) and week of the year. Based on the ginning data provided by the ginners, calculations were made for the time it took to process each bale (bph), defined as the time it took from seed cotton module to bale press, and for slowdowns, defined as bales with a processing rate between 2 and 60 min. Bales per hour were chosen to represent the ginning rate instead of seconds per bale because bph are conditionally approximately normally distributed. Slowdowns were considered in exploratory data analysis but were not modeled because they were rare events and there was insufficient data for a robust model. They were included in the bph model.

The exploratory data analysis and models developed for the detailed sensor and classing data suggested a high proportion of variability as explained by the field indicator variable (which can account for variance due to cotton variety, agronomic practices, harvesting, and weather). To include the impact of the seed cotton variety in the model development, a set comprising a variety of characteristics was defined and merged into the records, creating a data subset where a variety of information was present. Table 4 shows the various response variables tested for the data collected from the eight gins.

Modeling Methodology. The goal of modeling was not to determine which gins were inherently the fastest but to identify and understand in-season factors that contributed to ginning rate at a given gin. To use data from gins with different ginning capacities, all gin data were normalized to a z-score that was calculated using Equation 1 (Iverson, 2011).

$$z = (x-M)/SD \quad (1)$$

where x is the ginning rate per bale; M is the mean of the ginning rate for the season, and SD is the standard deviation of the ginning rate for the season.

The analysis framework was (1) variable selection, (2) iterative model assessment and selection, and (3) parameter interpretation. The final output variable is the ginning rate (bph); this is calculated as a function of the time from cutting a seed cotton module (debaling) to the final unit operation: compression of the fiber into a bale. The conditional distribution of bph was determined to be approximately normal.

Variable selection for data analysis and modeling was expert- and data-driven. The various criteria used for the variable section include: (1) resistance to data leakage (e.g., length uniformity can be

Table 3. Number of lint bales processed for the listed variety at the given gin in crop year 2021 (varieties with less than 500 bales not shown)

	Gin Identification								
Variety	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**All Gins**
A 9608 B3XF	571								571
CG 3527 B2XF						580			580
DP 1646 B2XF	1160	2794			24344	19465		48095	95858
DP 1725 B2XF						2801			2801
DP 1840 B3XF					444	2212			2656
DP 1845 B3XF					4429				4429
DP 1851 B3XF					568				568
DP 1948 B3XF					1671				1671
DP 2012 B3XF	478	1458			1133	10556		571	14196
DP 2020 B3XF	1176	4585			710	5760			12231
DP 2038 B3XF	1761	992				1170		4779	8702
DP 2115 B3XF		520			15	640		450	1625
DP 2127 B3XF		428				971		1579	2978
DP 2141NR B3XF						951			951
FM 1830 GLT					773				773
FM 1953 GLTP					4051				4051
FM 2398 GLTP					4730				4730
NG 4936 B3XF		241			7176	771		273	8461
NG 5711 B3XF					262			587	849
NG 5711 B3XF					1810				1810
PHY 312 WRF					688				688
PHY 332 W3FE					1360	45			1405
PHY 333 WRF					1187				1187
PHY 340 W3FE					1342				1342
PHY 350 W3FE		1293				216	215	1337	3061
PHY 360 W3FE		686				195		1084	1965
PHY 390 W3FE					3009				3009
PHY 400 W3FE		553			51994		390	1306	54243
PHY 430 W3FE								1072	1072
PHY 443 W3FE						324	129	167	620
ST 4990 B3XF	1277	1637						1446	4360
ST 5091 B3XF		1303		93	16				1412
Unknown	17929	20345	8951	91809	39800	14033	14565	19158	226590
Total	24352	36835	8951	91902	151512	60690	15299	81904	471445

heavily impacted by ginning rate, whereas length less so), (2) applicability to ginner and producer decision-making (e.g., the value chain can more easily influence variety characteristics than fields used for cotton production), and (3) quality of variable characteristics for modeling (preferring highly continuous, information-rich variables in cases of collinearity, such as that exhibited by strength). In addition to calculating bph, minimal data engineering was applied. Because seed cotton variety names were available for approximately 50% of the total bales in the data set, separate models were created for bales that contained variety characteristics and those that did not.

Seed cotton variety characteristic data were sourced from Bourland (pers. comm.) from field

Table 4. Various response variables tested in the analysis in year 2

Number of gins	**8; only data shared by 7 gins were used to model the ginning rate (bph). The 8th gin did not have enough information on the ginning rate and was not considered for the modeling studies.**
Number of gin-years	**12**
Number of lint bales processed	**581,000 (241,000 with cotton seed variety information)**
Variables	**USDA-AMS Classing office data, seed cotton variety characteristics data, some sensor data (IG[z], SJ[y]), weather data**
Objective	**Modeling and interpretability**

[z]IG: Sensors that are part of the Uster Intelligin system include sensors for moisture monitoring and estimates of leaf and trash content (Zellweger Uster, Inc., Knoxville, TN).

[y]SJ: Sensors manufactured by the Samual Jackson company for moisture management (Samuel Jackson Inc., Lubbock, TX).

trials in Kaiser, AR. To simplify variety information measured over multiple years, we derived a statistical mean of each phenotype for each variety. This mean was the best linear unbiased prediction (BLUP) derived from random effects models that treated each phenotype as a predictor and used variety name as the diagonal component on the variance components covariance matrix and year as the off-diagonal component (Proc Mixed, SAS Institute, Cary, NC). This estimation method shrinks or brings the phenotype estimates closer to the grand mean, with the greatest degree of shrinkage imposed on the least replicated varieties. This random effect model was chosen to be suitable for the low-replication, unbalanced design of these phenotypic measurements and to set the stage to extrapolate the ginning rate (bph) across the population of varieties' phenotypes. Table 5 gives the final variable selected for modeling the process.

Model accuracy was assessed through the validation partition's root mean squared error (RMSE); low RMSE values show that the model makes more accurate predictions and fits the data well. Chai and

Table 5. Variables engineered for inclusion in models

Variable name	**Variable description**
Bales per hour (Gbph)	**Target variable for gin rate**
Leaf Pubescence (LPub)	**Variety characteristic: Measure of leaf hairiness and data in this study were based on a visual rating on a scale of 1 (smooth leaf) to 9 (pilose, very hairy) (Bourland et al., 2023)**
Bract Trichomes (Btri)	**Variety characteristic: Based on a bract from a 1st position white flower from 6 samples in four replicated plots that were examined for trichome density (number of trichomes/cm) (Bourland et al., 2023)**
Lint Percent (LP)	**Variety characteristic: Based on variety trial data where 40 bolls were ginned to determine the mass of lint and seed, and the lint percentage was calculated as the mass of lint divided by the mass of seed cotton times 100 (Bourland et al., 2023)**
Fiber density (Fden)	**The number of fibers per mm2, estimated by dividing fibers per seed-by-seed surface area. Seed surface area (SSA) was estimated by the regression equation suggested by Groves and Bourland (2010): SSA = 35.74 + 6.59 SI, where SI is equal to the seed index associated with the sample (Bourland et al., 2023)**
Brand	**One or two letter code representing the brand marketing the variety (e.g. ST, DP)**
Week (ginweek)	**Week of year seed cotton bale was ginned**
GinID	**Gin number indicator**
Micronaire (MIC)	**Classing office: The measurement is based on the permeability of cotton by passing compressed air through compressed cotton specimens of fixed weight and fixed volume. The airflow permeability through the cotton sample is expressed as micronaire (Delhom et al., 2020)**
Extraneous Matter (EM)	**Classing office: Extraneous matter is any substance in cotton other than fiber or leaf. Examples of extraneous matter are bark, grass, spindle twist, seedcoat fragments, dust, oil, and plastic**
Reflectance (Rd)	**Classing office: Measures the brightness of the cotton**

Table 5. continued

Variable name	Variable description
Yellowness (+ b)	Classing office: Indicates the intensity of yellow shades. The color grade of cotton is determined by the degree of reflectance (Rd) and yellowness (+ b) as established by official standards (Delhom et al., 2020)
Trash	Classing office: Trash in cotton lint is the non-fiber particles that remain in cotton after the ginning process, such as leaf, seedcoat, bark, grass, and dust (Delhom et al., 2020)
Length	Classing office: The upper half mean length is measured by passing a small quantity of paralleled fibers known as a beard through an optical scanner within the HVI instrument system. Fiber length is reported as the average length of the longer half of the fibers (upper half mean length) (Delhom et al., 2020)

Draxler (2014) concluded that RMSE is more appropriate to represent model performance. In the present study the following criteria were used to understand the adequacy of the models developed: (1) lower RMSE, (2) showing a plausible sign (direction of effect) for each parameter, and (3) containing the maximum number of variables showing a suitable level of informational importance (e.g., statistical significance or variable importance). SAS® Viya® 3.5 Statistical software, SAS, Cary, NC was used in the present analysis.

RESULTS

Descriptive Statistics. Table 6 shows the number of bales processed by each gin and the percentage of seed cotton modules receiving extraneous matter calls in 2021 based on the USDA classing office data. The average weight of the ginned seed cotton or lint bales was 470 to 498 lbs (213-226 kg). The lowest weight bales were observed for Gin 4 (213 kg) and the highest for Gin 8 (226 kg). Out of the total processed by the eight gins, 42% of the processed seed cotton modules had variety information available. The characteristics of seed cotton varieties encompass several key attributes: fiber density, lint percentage, leaf pubescence, and bract trichomes. For the varieties ginned, fiber density ranged from 127 to 207 fibers per mm^2; lint percentage varied between 34 and 49%; leaf pubescence was in the range of 1 to 7, indicating a transition from smooth to very hairy surfaces; and bract trichomes per cm ranged from 14 to 62.

Table 6. Total bales processed, bales with extraneous matter (EM), and average bale weight for 8 gins for crop year 2021

Gin No.	No. of bales processed	Bales with EM (%)	Average bale weight
			lbs (kg)
1	24,352	0.11%	493 (223)
2	36,923	0.04%	497 (225)
3	8951	0.07%	489 (221)
4	91,910	5.63%	470 (213)
5	> 100,000	2.51%	487 (221)
6	61,199	1.51%	498 (226)
7	15,299	0.35%	497 (225)
8	82,229	2.04%	498 (226)

Table 7 shows the USDA Classing Office fiber quality data as measured by High-Volume Instrumentation, averaged across all varieties for the 2021 crop year. The color grade varied between white grades 21 and 41. The leaf grade values ranged between 3 to 4.1. The micronaire values were 4.23 to 4.60 for all the gins except Gin 6, where the micronaire was 3.85, likely due to environmental conditions in the region of that gin in 2021. Except for Gin 6, the average micronaire values were in the base range (no discount or premium). The fiber strength was 29 to 31.5 grams/tex, in the strong and very strong range. The loan values were highest for Gins 1, 2, and 5, whereas Gins 6 and 8 had the lowest. The upper half mean length was in the range of 29.21 to 30.73 mm (1.14-1.21 in). Seed cotton processed by Gin 3 and 8 had the highest upper half mean length. Changes in the lint quality from the various locations can be due to environmental factors during the cotton growing and ginning season or unit operations, such as the number of precleaning and lint cleaning operations used during ginning. The data in Table 7 is representative lint quality data from across the cotton belt and as presented by Cotton Incorporated for the fiber properties of the cotton grown in different regions in 2023 and 2024 (Cotton Incorporated, 2025).

Ginning Rate (BPH) Distributions and Derivation of the Response Variable. Figure 2 compares the kernel distribution of the ginning rate for all gins in the study for the crop year 2021. The y-axis represents the percentage of bales ginned at that rate per hour. The distribution mode for Gin 8 indicates

Table 7. Mean (± standard error) HVI lint properties for 8 gins providing data for this study for 2021 crop year[z]

Gin No.	Mic	Str (g/tex)	Rd	+b	CG	% TA	LG	UHML (mm)	UI (%)	LV (cents/lb)[y]
1	4.47±0.28	30.7±1.1	76.9±1.7	7.9±0.6	31-2	0.35±0.12	3.0±0.6	29.21±1.27	81.1±1.0	3
2	4.39±0.35	29.6±1.1	79.1±1.7	7.5±0.6	31-1	0.36±0.13	3.0±0.7	28.96±1.27	81.2±0.9	3.4
3	4.60±0.27	30.7±1.1	76.6±2.5	7.7±0.6	31-2	0.45±0.13	3.5±0.6	30.23±1.27	82±0.8	2.9
4	4.23±0.27	29.3±1.5	77.4±2.8	7.4±0.7	41-1	0.37±0.14	3.1±0.7	29.21±1.27	81±1.2	2.3
5	4.36±0.31	31.1±1.4	78.5±2.1	8.5±0.6	21-2	0.37±0.15	3.1±0.7	29.72±1.27	81.5±0.7	4.1
6	3.85±0.34	30.1±1.2	78.1±2.4	7.1±0.6	41-1	0.45±0.13	3.7±0.7	29.72±1.27	80.9±0.9	1.6
7	4.52±0.27	30.8±1.4	77.3±2.0	7.5±0.6	41-1	0.45±0.17	3.3±0.7	29.21±1.27	82.1±1.2	2.7
8	4.47±0.31	31.5±0.9	76.9±2.0	7.7±0.5	31-2	0.61±0.18	4.1±0.7	30.73±1.27	82.4±0.9	2.0

[z]Abbreviations: Mic, Micronaire; Str, Strength; Rd, Reflectance; + b, yellowness; CG, Color grade; % TA, percent trash area; LG, Leaf grade; UHML, Upper half mean length; UI, Uniformity index; LV, Loan value

[y]Loan value above the base value of the cotton

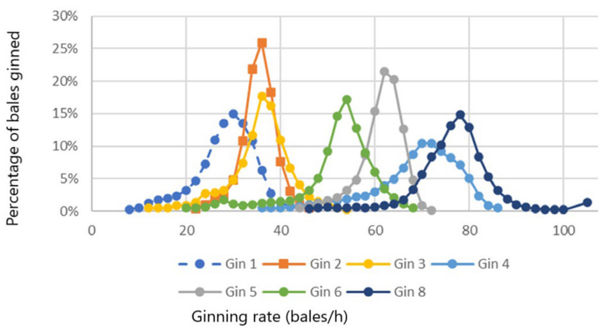

Figure 2. Bales per hour histograms by gin for crop year 2021 (ginning rate normalized to a 500 lb or 226 kg lint bale).

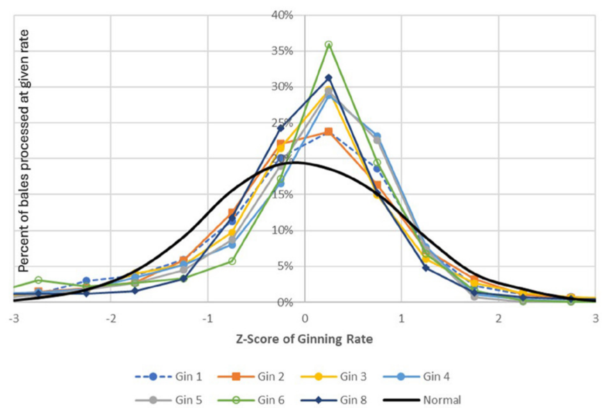

Figure 3. Bale per hour (bph) or ginning rates z-score for gins in the study for the crop year 2021.

its higher overall ginning rate, and wider distribution represents higher variance. Figure 3 compares the z-score ginning rate for each gin and shows that all the gins in the study had a slight left skew and were slightly kurtotic ginning rate distributions. The model accounted for the left skew by taking the best linear unbiased prediction (BLUP) of sources of bale rate variance and identifying extremely low residual (very slow) bales and removing them from the analysis. These bales only occurred on a few discrete days in gins and thus were considered products of mechanical malfunction or other operational interruptions and not valid samples. The kurtosis/non-normality observed in the raw data was not observed in any model's residual distribution.

Figure 4 shows the ginning rate (i.e., bph by gin-year). In Fig. 4, Gin 1 had records that met our modeling requirements for the crop years 2018 to 2020. In contrast, the other gins were invited to participate in 2020, so the data presented to those gins only pertain to the 2021 crop year. The current analysis focused on using z-distributions as the ginning rate (bph) response variable. To further diminish randomness and enhance model precision, the bale rate used for the z-score was the BLUP of the raw bale rate computed from the week of ginning and bale weight (Fig. 4). This means a bale with two standard deviations (z) above the mean for Gin 1 or Gin 8 should represent the 97.9th percentile of bale rate at each gin, even though the Gin 8 bale was processed approximately four times faster than Gin 1. Furthermore, because the time of year of ginning and bale rate explain the variance but are not of particular interest, each bale's z-score was calculated from a BLUP of bale weight and week within the gin.

A directed acyclic graph was constructed (Fig. 5) to represent variable hierarchies with respect to analysis intent. The gin rate, the dark green box, is the response variable. The lint moisture content was not part of Fig. 5 as the lint moisture content data collected were not consistent for the different gins; instead, we used reflectance (Rd) and yellowness (+b) as surrogates for lint moisture content as ini-

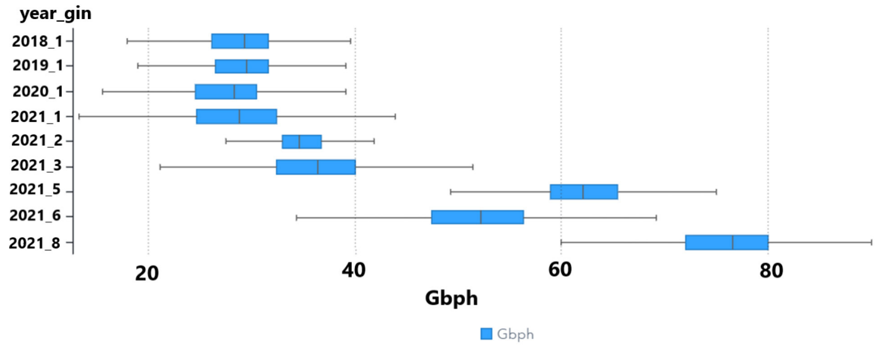

Figure 4. Observed ginning rate (bales per hour [GBPH]) by gin-year. Boxes represent 25th and 75th percentiles centered on median, and whiskers the values outside of the interquartile range.

tial analysis showed a correlation. Light blue boxes represent random effects, BLUP values, that affect gin rate but are not the subject of the study. Dark blue boxes represent potential fixed effects, model explanatory variable types considered in the main analysis. Cotton growing conditions and weather, while important in affecting ginning rate, were not used in the model development directly due to a lack of generalizability and incoming data precision, respectively. The ginning rate z-score (bph) was the response for variety and fiber quality fixed effects. Subsequently, the residual of this fixed effect model was used as the response variable for a model of the partial variety of data available.

Following the roadmap in Fig. 5, a selection of individual variables was made for modeling the ginning rate. Figure 6 shows the parameters considered and those used to model the ginning rate (bph). Gin-specific factors were considered, including time of year, represented by the week of ginning, ginning rate (bph), and slowdowns. Week (ginweek), bale weight (GbaleWT), and gin (GinID) were factored in by creating a BLUP of gin rate, centered and standardized (z-score) (z-gbph). Grower data (grower, farm, and field IDs) and weather variables were excluded in favor of including more proximate surrogates in the gin rate. Variables capturing a variety of attributes, Rd and +b (surrogates for moisture), and quality parameters such as micronaire, reflectance, and trash with extraneous material were hypothesized to impact the ginning rate (bph).

Data Modeling. Ginning rates based on the BLUP model were calculated based on week, year, bale weight, gin, and the bale rate z-scores (z-gbph). Figure 7 is a scatter distribution representing the BLUP model output prediction and residual. The results show a good fit, where the maximum of the predicted values was around the center, with most bales within 10 bph of their prediction. In general, most modern gins can process as many as 60 bph (National Cotton Council of America, 2025), but this depends on a number of factors such as variety, harvesting method, lint properties, and type of ginning method used; currently, some gins in the U.S. process

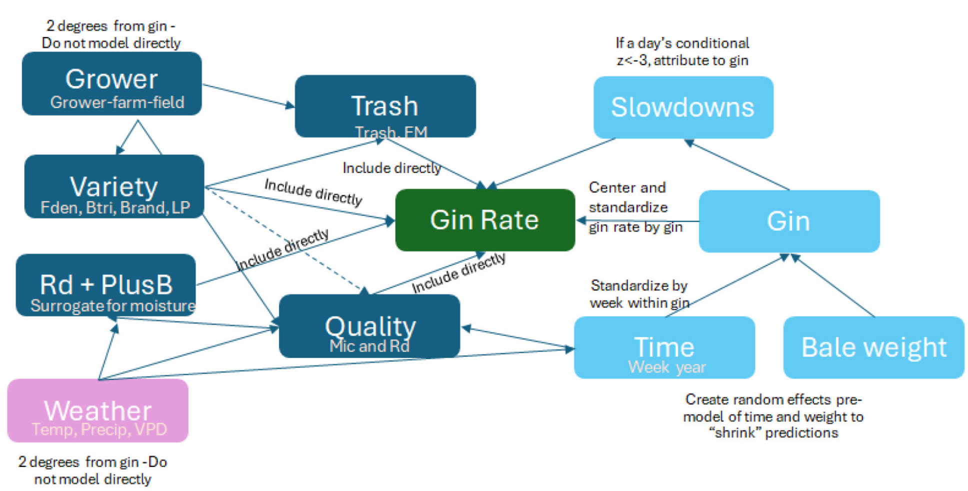

Figure 5. Directed acyclic graph indicating hypothesized relationships, presented in a hierarchy.

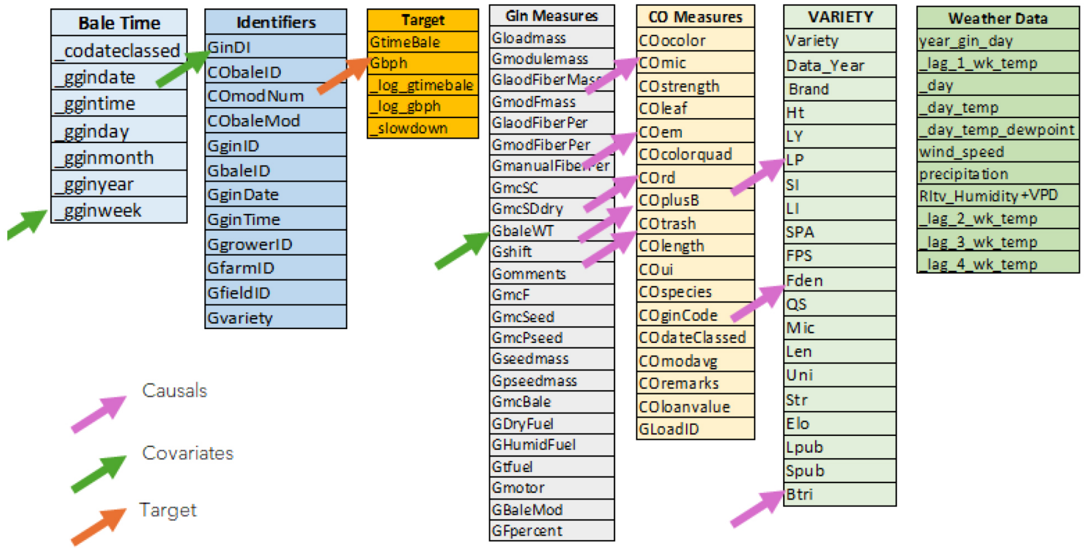

Figure 6. Major variables selected for parameter model development.

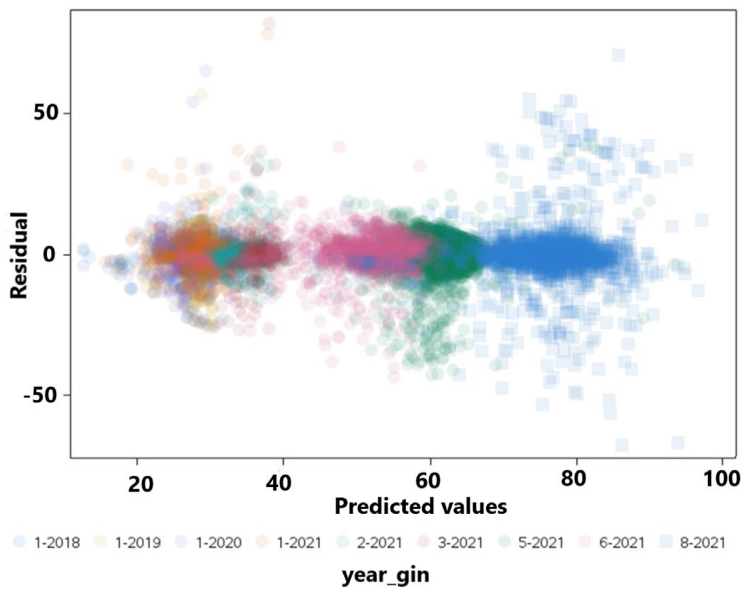

Figure 7. Predicted ginning rate and residual values by gin number-year from Model 1, a random effects model intended to normalize bale rate (predicted, "Pred," bales per hour) across gins, years, bale weights and times of year within the gin. High transparency was applied to the data to minimize the obfuscation among the hundreds of thousands of data points. The residuals, observed bale rates minus model-predicted bale rates, were suitably distributed to maintain an assumption of independence among gin-years.

approximately 75 bph. The model also showed acceptable normality and homoscedasticity, albeit with a tendency for the slowest bales (lowest residuals) to be underpredicted at faster gins. This prediction model can be further improved by including other variables, such as seed cotton moisture, as one of the parameters to improve prediction efficiency. All predicted values were next-centered and standardized (i.e., z-scores created) for use as the target in Model 2.

Lint Quality Effects on Ginning Rate. A parametric model was developed for the z-score of the ginning rate incorporating quality parameters such as micronaire, Rd, +b, trash, and extraneous matter (EM) as fixed effects (Table 8). The model parameter estimates are indicated in Table 8. All variables were highly statistically significant ($p < 0.0001$) (Table 8). The standard error values were consistently lower for all lint attributes, with the exception of micronaire, which indicates a higher level of precision in

Table 8. Parameter estimates for lint quality effect on bale rate z-score

Parameter	DF	Estimate	Standard error	95% confidence limits		Chi-square	Pr>ChiSq
Intercept	1	-13.96	0.4828	-14.908	-13.015	836.06	<0.0001
EM Present[z]	1	-0.15	0.0110	-0.1744	-0.1311	191.88	<0.0001
EM Not Present[y]	0	0	-	-	-	-	-
Micronaire	1	3.27	0.1096	3.0574	3.4871	891.25	<0.0001
Rd	1	0.18	0.0062	0.1722	0.1967	876.38	<0.0001
+ b	1	0.048	0.0021	0.0440	0.0522	528.41	<0.0001
Trash	1	0.032	0.0010	0.0296	0.0338	873.74	<0.0001
Rd×Mic	1	-0.044	0.0014	-0.0472	-0.0417	984.29	<0.0001
Dispersion	1	0.99	0.0022	0.9847	0.9934	-	-

[z]Extraneous matter (EM) Present: assigned a value of 1 if the bale received any EM designation

[y]EM Not Present: assigned a value of 1 if no EM call was received

Table 9. Parameter estimates for seed cotton variety attributes effect on bale rate z-score

Parameter	DF	Estimate	Standard error	95% confidence limits		Chi-square	Pr>ChiSq
Intercept	1	-13.102	0.1543	-13.405	-12.800	7204.02	<0.0001
Group_Variety A	1	-3.9936	0.1065	-4.2024	-3.7849	1405.88	<0.0001
Group_Variety AM	1	-1.7659	0.2889	-2.3322	-1.1995	37.35	<0.0001
Group_Variety CG	1	-1.2578	0.1324	-1.5174	-0.9983	90.25	<0.0001
Group_Variety_DG	1	-1.6032	0.0404	-1.6824	-1.5240	1574.06	<0.0001
Group_Variety DP	1	-1.3726	0.0278	-1.4271	-1.3181	2434.15	<0.0001
Group_Variety FM	1	-1.1954	0.0658	-1.3246	-1.0663	329.13	<0.0001
Group_Variety NG	1	-0.2431	0.0333	-0.3084	-0.1777	53.18	<0.0001
Group_Variety PH	1	-1.9330	0.0277	-1.9874	-1.8787	4861.33	<0.0001
Group_Variety ST	0	0	-	-	-	-	
LP	1	0.49271	0.00364	0.4855	0.4998	18305.73	<0.0001
Fden	1	-0.0470	0.00058	-0.0481	-0.0458	6501.77	<0.0001
Btri	1	0.01551	0.00125	0.0130	0.01797	152.07	<0.0001
Dispersion	1	4.12439	0.01348	4.0980	4.15092	-	-

the estimation of those coefficients. Conversely, the elevated coefficient value for micronaire suggests a more substantial relationship with the ginning rate (Table 8). The sole main-level negative parameter estimates (i.e., associated with slower ginning) was the presence of EM. Micronaire had a positive parameter estimate (equivalent to every incremental increase in micronaire associated with bale rate three standard deviations faster). This is unsurprising given that low micronaire is typically associated with a slower ginning rate, mainly due to a higher number of immature fibers in the seed cotton. Notably, most (25th percentile) micronaire values in this data set were comfortably high at greater than 4.1; in general, if the seed cotton has higher amounts of immature fibers (which results in low micronaire values), the ginning rate can be decreased due to increased fiber entanglement and fiber breakage during the ginning process, leading to slower processing speeds and also the gin might have to work harder to separate the immature fibers, thereby reducing the overall efficiency and output rate. Our interactions with the ginners in the U.S. have corroborated this observation that low micronaire reduces the ginning rate.

The parameters Rd, +b, and trash were also positively associated with the ginning rate. In the present study Rd and +b were hypothesized as surrogates for seed moisture content, as it highly influences both these quality parameters and can influence the ginning rate; for example, higher seed cotton moisture increases +b and reduces Rd, and although high moisture is often associated with slower ginning, the limited moisture data from Gin 1 and Gin 8 suggested the seed cotton processed was at approximately 6%

wet basis (w.b.) moisture content. Thus, within seed cotton samples considered to be approximately 6 % (w.b.), a higher degree of moisture or weathering can support more efficient ginning. Higher trash can be a consequence rather than a cause of faster time to bale. Higher throughput rates in cotton gin machinery, especially lint cleaners, generally reduce cleaning efficiency (Mangialardi et al., 1994). The interaction term of Rd and micronaire (Rd ×Mic) shown in Table 8 was associated negatively with the ginning rate, perhaps representing an interaction of boll maturity with the gin rate, that is, immature bolls with bright, wet, and immature cotton might have reduced the ginning rate. The results of Model 2 were acceptably homoscedastic and normally distributed (including by gin), suggesting these parameters have widespread applicability across gins and regions of the U.S. cotton belt. The dispersion parameter of the model is below 1 within the upper 95% confidence limits, indicating that the model incorporating these quality elements predicts the bale rate across gins significantly better than random. However, because the dispersion parameter is numerically close to 1, the bale rate is unexplained primarily with respect to the model. Thus, an effort was made to see if unexplained variance could be explained using seed cotton variety information.

Variety Effects on Ginning Rate. The residuals (unexplained variance) from the model that accounted for gin identity, week of the year, bale weight, and classing characteristics were used as the target for a subsequent model incorporating seed cotton variety information. This tiered model approach was used because seed cotton variety information is present only for a fraction of the bales. Instead of modeling seed cotton variety directly, we used variables that describe seed cotton variety characteristics so the model could potentially be extrapolated to others, including future varieties.

Figure 8 represents the z-score of bales across all and a select seed cotton variety, respectively. Out of the total data analyzed, 73 seed cotton varieties had sufficient replication. Anecdotal evidence from ginners suggested ST4990 B3XF was slower (Fig. 8). These results corroborated that ST4990 B3XF was slower, and a directed acyclic graph was constructed (Fig. 9 a, b) that associated the categorical uniqueness of this variety with lower Fden and LP. This variety's slightly lower bract trichomes and much lower leaf pubescence would be predicted to offset the impact of sparser fiber densities. The ability to predict seed cotton variety impacts based on seed cotton characteristics is encouraging, as it points to the ability to build a model that is not based on variety names and should be able to predict the impact of new varieties based on their characteristics, providing useful guidance to breeding programs. Although conditionally normal (conditioned on continuous variety components LP, Fden, and Btri, but not seed cotton variety name), residuals appeared visually structured by brand (Fig. 10). Therefore, it was decided to include the brand in seed cotton variety models, hypothesizing the varieties have enough population substructure within breeding programs to maintain ginnability characteristics specific to the brand beyond LP, Fden, and Btri.

Table 9 shows the parameters for the third level of the model (Model 3) developed that account for variety (LP, Fden, Btri, and brand). Because residuals were used in this model, a negative parameter estimate indicates faster ginning than expected, given the above quality parameters. The model originally developed exclusively using LP, Fden, and Btri showed an unexplained residual structure that could be correlated to the first two letters of each seed cotton variety's name, thus the addition of "brand". The parameter estimates of the brand category are based on GLM (general linear model)-encoding, which references the alphanumeric last value, ST. Each brand was significantly faster (residuals more negative) than ST. High LP, often associated with smaller seed varieties, was negatively associated with gin rate, as was higher Btri, which could cause excess trash following cotton defoliation. Higher Fden was associated with faster ginning. It is important to note that these results reflect high variety-level estimate uncertainty and should not be used as the basis of seed cotton variety or brand selection decisions. Instead, these results could be used to target higher fiber density and lower bract trichomes, at least for a gin-friendly breeding program. Figure 11 shows the computer-based ginning rate calculator developed based on the lint quality and seed cotton variety characteristics for the convenience of the ginners. This calculator uses data on Rd, +b, and trash based on Model 2 and LP, Fden, Btri, and brand based on Model 3 to predict the ginning rate. This calculator can help the ginner predict the ginning rate based on seed cotton variety and lint quality attributes.

Other Findings (Gin Week, Seed Cotton Moisture, Rd, and +b Effect on Ginning Rate).

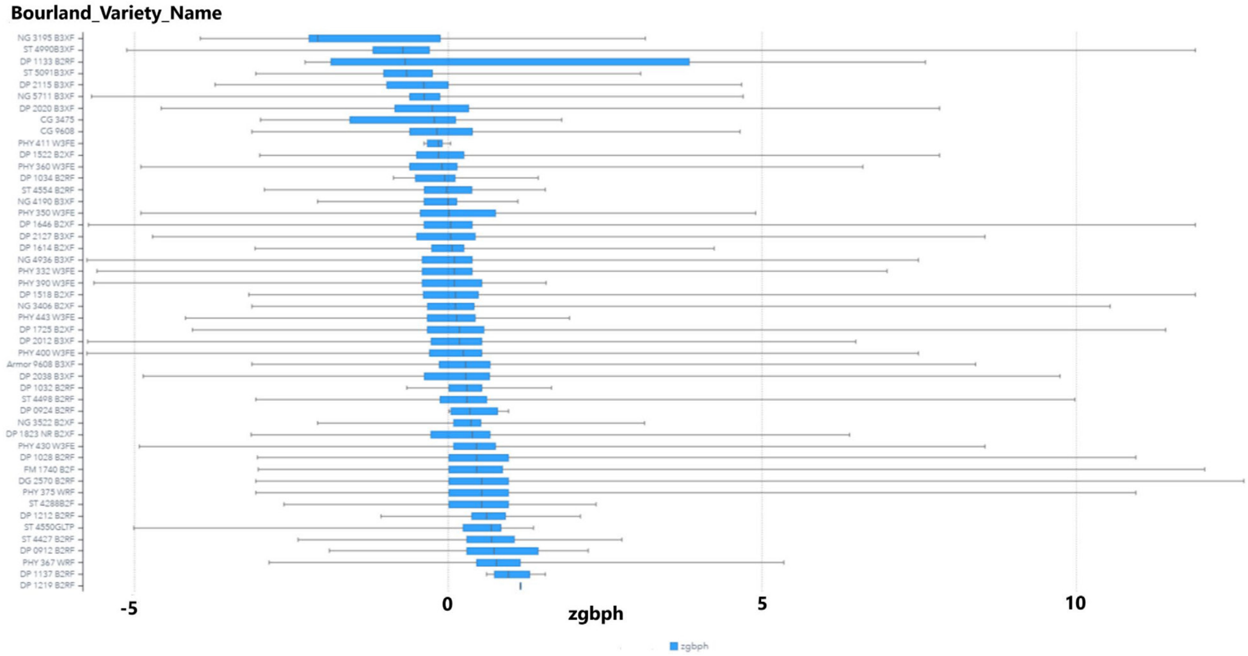

Figure 8. Model output showing the impact of variety on the ginning rate that has been normalized to a z-score (z-gbph) on the x-axis with variety name on the y-axis. Gray whiskers show values outside the interquartile range of z-values for a given variety, and blue indicates the 25th and 75th percentiles centered on median. Higher values indicate more bales per hour; ST4990 B3XF is the second-slowest ginning variety in this study on a median basis.

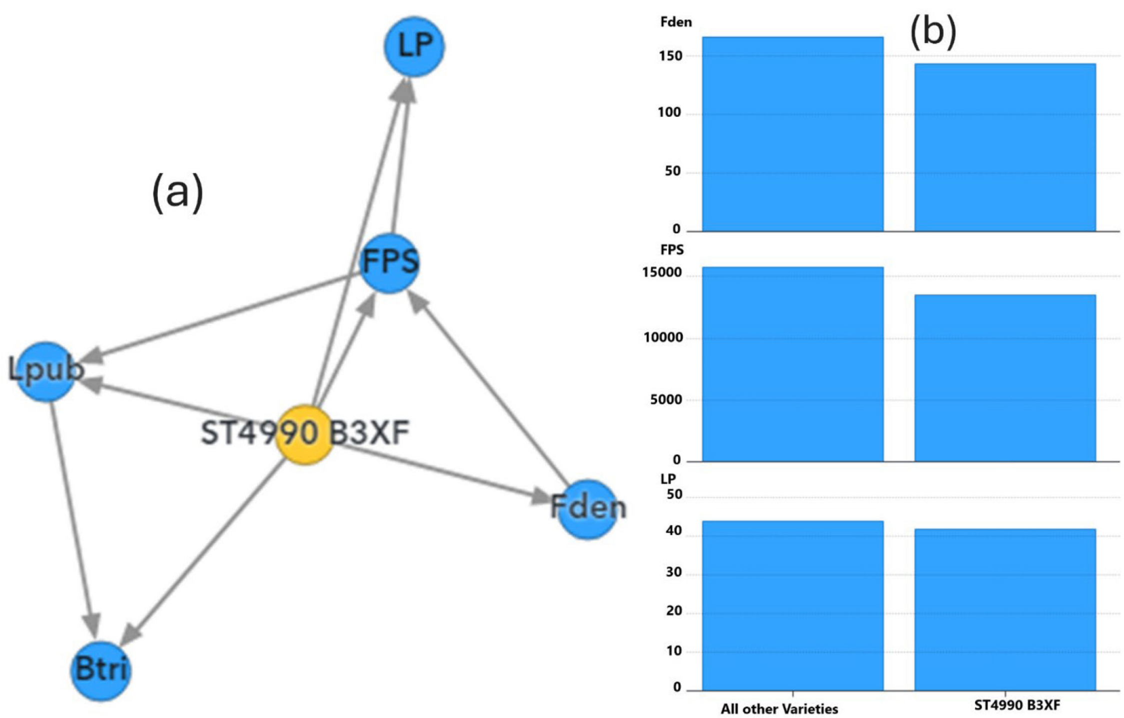

Figure 9. (a) Seed cotton variety characteristics that distinguish ST4990 B3XF: Fden is fiber density, Btri is bract tricoms, Lpub is leaf pubescence, FPS is fibers per seed, and LP is lint percentage. (b) Average values of Fden, FPS, and LP for all varieties in the study compared to the variety ST4990 B3XF; the sparse fiber density of this variety could explain the low ginning rate of this variety. Lower Lpub and Btri values of this variety (not shown) are expected to net improve this variety's performance.

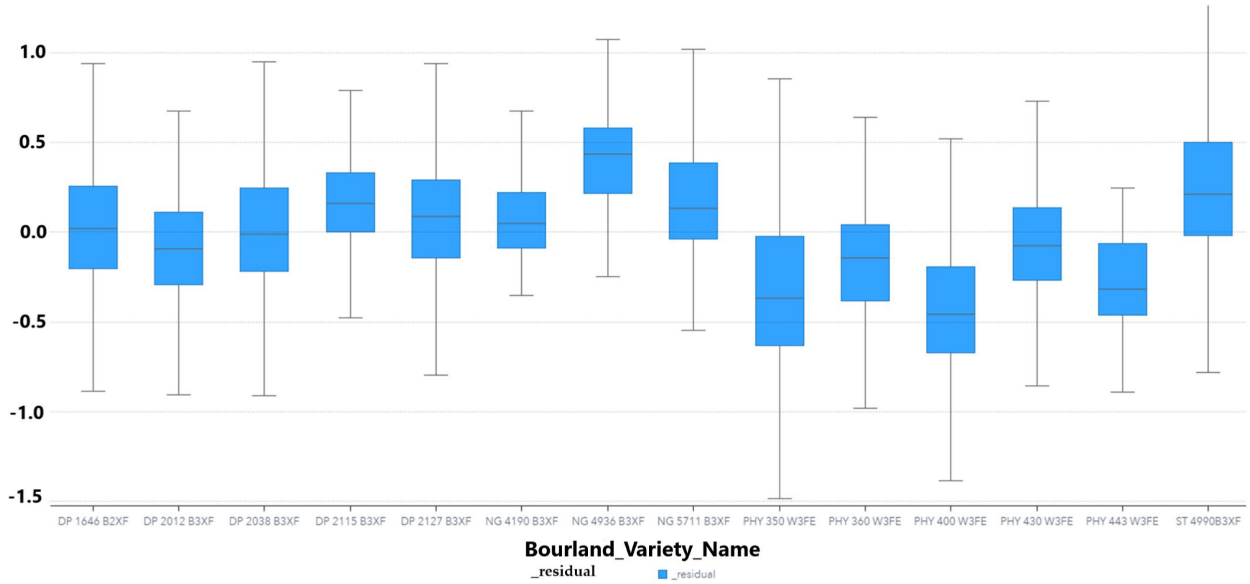

Figure 10. Residuals of normalized ginning rate derived from a model that factored in gin, time, cotton quality, and variety components. The residual is the observed minus model-predicted value of the normalized ginning rate, with lower-than-zero values representing over predictions and higher-than-zero values representing underpredictions. Residuals appear visually correlated to brand identity (first two letters of each variety name). The box represents the 25th and 75th percentile of residuals, centered on the median, and whiskers the range of values outside the interquartile range.

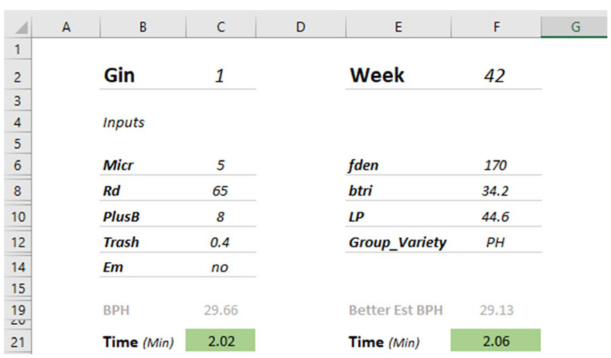

Figure 11. A computer-based ginning rate calculator based on lint properties and seed cotton variety attributes.

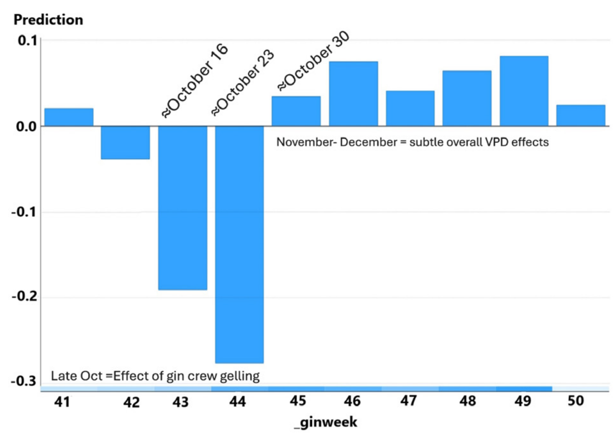

Figure 12. Impact of the ginning week on the ginning rate: Predicted bale rate z-score by week given gin, year, and bale weights. For context, Julian week 43 is approximately the third week of October (VPD = vapor pressure deficit).

The combined data set showed that the week of the ginning season (ginweek) was an important factor in predicting the ginning rate, with the first weeks of ginning being significantly slower across gins. It is hypothesized that this could be due to several factors, including the gin crew gaining experience as the season progresses, changes in weather conditions, or crop conditions. Figure 12 shows how the week of ginning impacts the ginning rate, where it is clear from the figure that in the initial weeks of ginning, the ginning rate is lower due to the gin crew getting together or gelling, in ginner parlance. Also, Fig. 12 indicates that the ginning rate decreases at the end of the ginning season, possibly due to mechanical or pneumatic issues in the gin.

The moisture of the seed cotton modules that was seen in the present study was in the range of 5 to 9% (w.b.); however, this data was only available for two gins. For Gin 8, a partial dependence plot showed that at moisture greater than 8.5% there is a steep drop in the ginning rate (Figs. 13 and 14). Figures 13a and b show the seed cotton moisture distribution based on the data available at Gins 1 and 8, and Fig. 13b illustrates the heat map based on the raw data relationship between moisture and ginning rate z-scores. It is clear from the figures that a wide distribution can be seen in moisture. A partial dependence plot

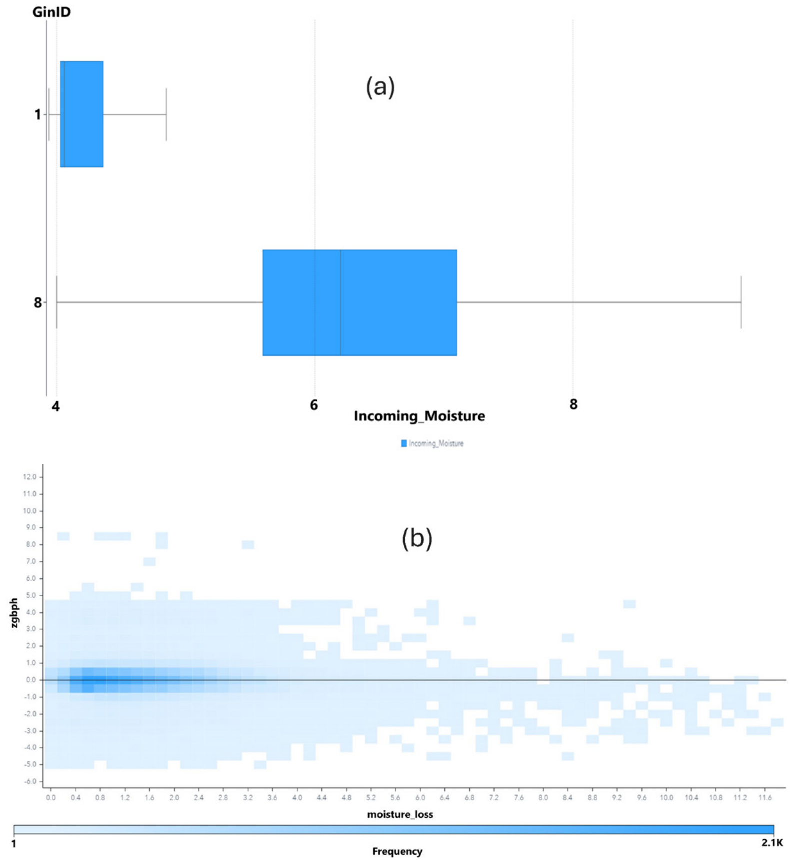

Figure 13. (a) Moisture effects: Distribution of seed cotton moisture for Gins 1 and 8. (b) Heat map illustrating raw data relationship between moisture and ginning rate z-scores.

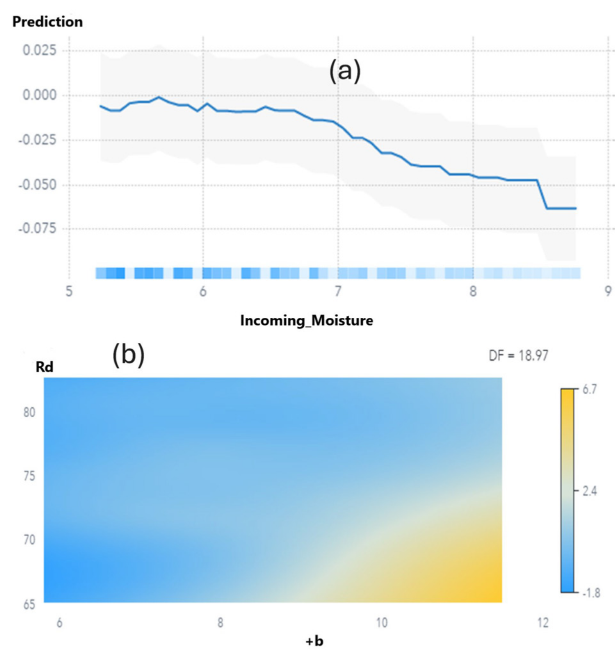

Figure 14. Moisture effects on the ginning rate. (a) Post-modeling partial dependence plot for moisture effect on the ginning rate z-score from Gin 8. (b) Spline plot demonstrating relationship between Rd, +b, and moisture (low Rd and high +b associated with higher moisture seed cotton). Due to data availability, Rd and +b were used as moisture surrogates in Model 2. Note: Incoming moisture reported is based on a wet basis.

(Fig. 14a) shows moisture in the range of 5 to 6.5 % (w.b.), resulting in a stable ginning rate, whereas if the incoming moisture is higher than 6.5%, there is a drop in the ginning rate. Additionally, with the uncertainty of the calibration of the moisture sensors at both gins, the absolute moisture values reported here should not be assumed to be accurate and further research should be done to validate this observation. Ultimately, because seed cotton moisture data were available only from two gins that appeared poorly calibrated to one another, surrogate variables of Rd and +b were considered to represent moisture in an interaction. Figure 14b demonstrates a generalized additive model spline contour plot illustrating the relationship between Rd, +b, and moisture at the two gins.

DISCUSSION

The data that is currently captured by most ginners is not complete enough to develop models for the ginning process to predict gin profitability. Instrumenting a commercial gin and collecting the right information from a modeling point of view is critical to inform the ginners on process efficiencies with respect to seed cotton varieties, lint properties, especially moisture content, and gin unit operation parameters such as motor power and temperature, and fuel usage.

The gins in the U.S. have different moisture sensors (microwave, Samuel Jackson, Intelligin, and others) to measure seed cotton and lint moistures and each sensor has its own calibration methodology, and accuracy range. Developing a standardized moisture sensor and calibration technique with the desired accuracy that the gins in the U.S. can use can help get uniform moisture data to understand the impact of seed cotton moisture on the ginning rate and can help develop a robust generic ginning rate model (bph) with respect to incoming seed cotton module moisture.

For example, it has been identified that biobased material processing rates and product quality are primarily influenced by moisture. The moisture in the seed cotton can strongly impact precleaning and ginning unit operations in cotton ginning. Gin drying systems remove excess moisture only from the lint fraction, but not the seed fraction, of seed cotton. Seed cotton moisture content is a function of ambient relative humidity and is influenced also by ambient temperature as well as moisture changes in the seed cotton modules during storage. The changes in seed cotton moisture can result in color degradation and mold if stored for extended periods and higher than recommended moisture contents. The color changes in seed cotton modules can depend on various factors, such as the distribution of various components of seed cotton; for example, if seed cotton has a higher moisture content during harvest, the post-storage quality will be more impacted negatively compared to the dry harvest. It has been hypothesized that if seed moisture is high at harvest, but lint and trash are low in moisture, moisture in the seed can move into lint and trash, causing degradation of lint color parameters.

Ginning studies have indicated that raising dryer temperature can influence cleaning efficiency (Boykin, 2005) because the amount of trash removed by cylinder cleaners and stick machines strongly depends on seed cotton moisture content. We also believe that incoming seed cotton moisture (which includes moisture of seed, trash, and lint) strongly influences ginning rate (the key predictor of gin profitability). Therefore, we believe that changes in cotton seed moisture can impact ginning rate, energy consumption, lint quality, and gin profitability. Based on these factors, there is a need to develop a fundamental model or model based on the first principles valid across gins for relating seed cotton moisture to the ginning rate. Further, this model should be expanded to include lint quality and seed cotton variety characteristics (LP, Fden, and Btri) to improve model robustness and predict the ginning rate accurately.

Based on analysis of commercial gin data, it has become apparent that the various original equipment manufacturers (OEM) and sensor platforms are not aligned in a manner that allows for easily combining these various data streams into a continuous dataset for data science analysis using machine learning or artificial intelligence (AI), methodology. For example, one OEM sensor is tied to bales but does not take its index update from the bale tag reader. Instead, it reads the limit switch on the bale-press system, and this can and does frequently get out of alignment with actual bale tags. This results in unreliable mechanisms to tie data to the cotton bale, a critical link as the cotton bale is classed by the USDA-AMS classing office, providing fiber properties that are critical modeling inputs. Aligning the sensor data to each bale ID number via a bale tag reader and an accurate and aligned timestamp can help to collect more reliable data. Some gins are implementing a programming solution for the OEM sensor to address this challenge. Another source of error occurs when changing from daylight savings time, as some OEM clocks will make this change, but many microcontroller-based systems will not. Each sensor's time variations, drift, and fluctuations create a fractured dataset, making it difficult to align with sufficient accuracy for high-quality modeling. As such, we would encourage OEMs to use coordinated universal time (UTC) to a universal standard that all computer systems and programming languages support. Further, with modern systems invariably tied to the internet, it is possible to go one step and use UTC and Network Time Protocol (NTP) to keep their system clocks aligned. Even microcontrollers now have public domain libraries that make this straightforward. The sooner the gin industry can get this standardized, the easier it will be to develop a robust AI model that the ginning industry can use in the U.S.

CONCLUSIONS

Understanding factors such as lint quality attributes, seed cotton variety characteristics, lint moisture content, and ginning week's impact on the ginning rate is critical for ginners and farmers. Based on this study, the following conclusions were drawn: (1) the lint quality attributes of cotton processed by eight different gins indicated that the upper half mean length was in the range of 1.14 to 1.21 in (28.96-30.73 mm), uniformity index was approximately 80.9 to 82.4%, color grades were 21 to 41, strength was between 29.3 and 31.5 g/tex, and micronaire was between 3.85 and 4.47; (2) the seed cotton variety analysis indicated that out of 73 varieties in the data set for eight gins that had sufficient replication to classify, 40 varieties ginned slower than the study means, and 11 had faster ginning rates. Therefore, variety can have a significant impact on ginning rates; (3) the modeling approach, where the data were normalized by gin, week of the year, and bale weight, and the ginning rate was based on ginning week, indicated that the ginning rate is lower in the first three weeks and at the end of the ginning season compared to the middle of the ginning season (weeks 4-8); and (4) the parametric models developed for lint quality (micronaire, Rd, +b, and trash) and the variety (LP, Fden, Btri, and Brand) can predict gin rate (bph) to a low level of precision. These observations from real-world data can be used to breed cotton varieties with the desired attributes and lint quality properties to improve the ginning rates.

DISCLAIMER

The findings and conclusions in this publication are those of the author(s) and should not be construed to represent any official USDA or U.S. government determination or policy. Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the USDA. USDA is an equal opportunity provider and employer.

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