Field Crops Research 315 (2024) 109483

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Planting for perfection: How to maximize cotton fiber quality with the right planting dates in the face of climate change

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A R T I C L E I N F O

Keywords:
Fiber quality
Fiber strength
Fiber length
Fiber micronaire
Fiber uniformity
Genetic algorithm
Growing degree days
Spatial analysis

A B S T R A C T

Context: Cotton quality is as crucial as cotton quantity. Despite considerable efforts to enhance cotton yield, there has been limited focus on maximizing fiber quality. The temperature experienced from flowering to boll opening becomes the critical factor affecting fiber quality when cotton is cultivated under optimum water and nutrient conditions. This depends on the planting date for a specific location and cultivar. Therefore, fiber quality can be improved by optimizing the planting date for a specific geographic location and cultivar.

Objective: The study aims to develop a methodology for optimizing planting dates to maximize fiber quality, taking into account location-specific weather and cultivar details.

Methods: A methodology is developed and demonstrated for the cotton belt in the USA. The methodology accounts for temperature, planting intervals, cotton varieties (early, mid, and late-season), and four major fiber quality indicators (fiber length, strength, micronaire, and uniformity). Based on the average of the last 15 years of weather data and different cotton cultivars, spatial maps depicting the best planting dates and associated fiber quality are analyzed for 765 cotton-growing counties in the USA. The study also explores variability in the optimum planting date and fiber quality with climate change in these counties.

Results: Results indicate that planting cotton at the optimum planting date can improve all fiber quality features. Fiber length can range from medium (25–29 mm) to long (30–34.5 mm), fiber strength from strong (29–30 g/tex) to very strong (>31 g/tex), micronaire from the discount range (≤3.4 and ≥5.0) to the base range (3.5–3.6 and 4.3–4.9), and uniformity can be high (>85). Applying the methodology with consideration of future climate projections shows a 19 % decline in micronaire - the most affected trait, followed by 8.4 % and 1.6 % decreases in length and uniformity, respectively. In contrast, fiber strength is expected to increase by 5 % in the future.

Conclusions: Results indicate that optimizing the planting date with the developed methodology can enhance fiber quality. Additionally, the methodology can predict variations in fiber quality due to future climatic conditions.

Significance: The developed methodology can be valuable for farmers and growers seeking to enhance fiber quality. It is standard and applicable to any location and cultivar. A similar approach can be adopted for other locations and crops, such as soybeans, rice, and wheat, to optimize their quality.

1. Introduction

Approximately 25 million tons of cotton are produced annually worldwide, contributing significantly to the global economy, with an estimated annual economic impact of at least $600 billion (Khan et al., 2020; Tokel et al., 2022). Cotton quality plays a pivotal role in the cotton production sector, impacting both cotton growers and industries alike (Wang et al., 2020). Poor cotton fiber quality can pose challenges during processing and result in financial losses for both producers and manufacturers (Beegum et al., 2023a; Bradow and Davidonis, 2000). In the USA, the produced cotton is subjected to quality evaluations regulated by the United States Department of Agriculture-Agricultural Marketing

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https://doi.org/10.1016/j.fcr.2024.109483
Received 15 March 2024; Received in revised form 18 June 2024; Accepted 25 June 2024
Available online 4 July 2024

Service (USDA-AMS), based on which high-quality fibers are rewarded with premium rates, while lower-quality fibers are penalized with discounts (Ge et al., 2008; USDA, 2001).

Numerous research studies, both experimental and modeling, have focused primarily on increasing the quantity (yield) of cotton. In contrast, only limited studies have examined enhancing cotton quality (Beegum et al., 2023a; Bradow and Davidonis, 2000; Thorp et al., 2014). This is due to the complexity of understanding different factors influencing cotton quality. The first cotton crop models were developed in the early 1970s, but it was only in 2023 that a fiber quality model was developed (Baker et al., 1983; Beegum et al., 2023a, 2023b; Hearn, 1994; Jones et al., 1974; Thorp et al., 2014; Wall et al., 1994). This highlights the insufficient attention given to the study of cotton fiber quality.

Cotton fiber quality is influenced by a range of factors, including planting date (Beegum et al., 2023a; Davidonis et al., 2004), water and nutrient availability (Lokhande and Reddy, 2014b; Ul-Allah et al., 2021; Wang et al., 2016), temperature (Lokhande and Reddy, 2014a; Pettigrew, 2008), cotton cultivar type (Hussain et al., 2022; Khan et al., 2020), and the growth and developmental stages of the plant (Davidonis et al., 2004; Pettigrew, 2001; Reddy et al., 2004). When there is an adequate supply of water and nutrients, the predominant drivers of fiber quality become temperature and cultivar selection. Temperature variations are primarily influenced by the chosen planting date; therefore, optimizing the planting date can significantly contribute to improving fiber quality.

Numerous studies have explored the impact of varying planting dates on fiber quality. For instance, Wrather et al. (2008) examined the effect of planting date and plant population on fiber quality (Wrather et al., 2008). Mauget et al. (2019) investigated the effect of planting date on the quality of cotton grown in the southern high plains of the USA (Mauget et al., 2019). Davidonis et al. (2004) evaluated fiber quality in relation to boll location and planting date, while Pettigrew et al. (2001) studied the effect of seed quality and planting date on lint quality (Davidonis et al., 2004; Pettigrew, 2001). However, most of these studies have been confined to specific cultivars, certain plant growth and development features, particular years, and locations. Consequently, our understanding of how factors such as cultivar selection,

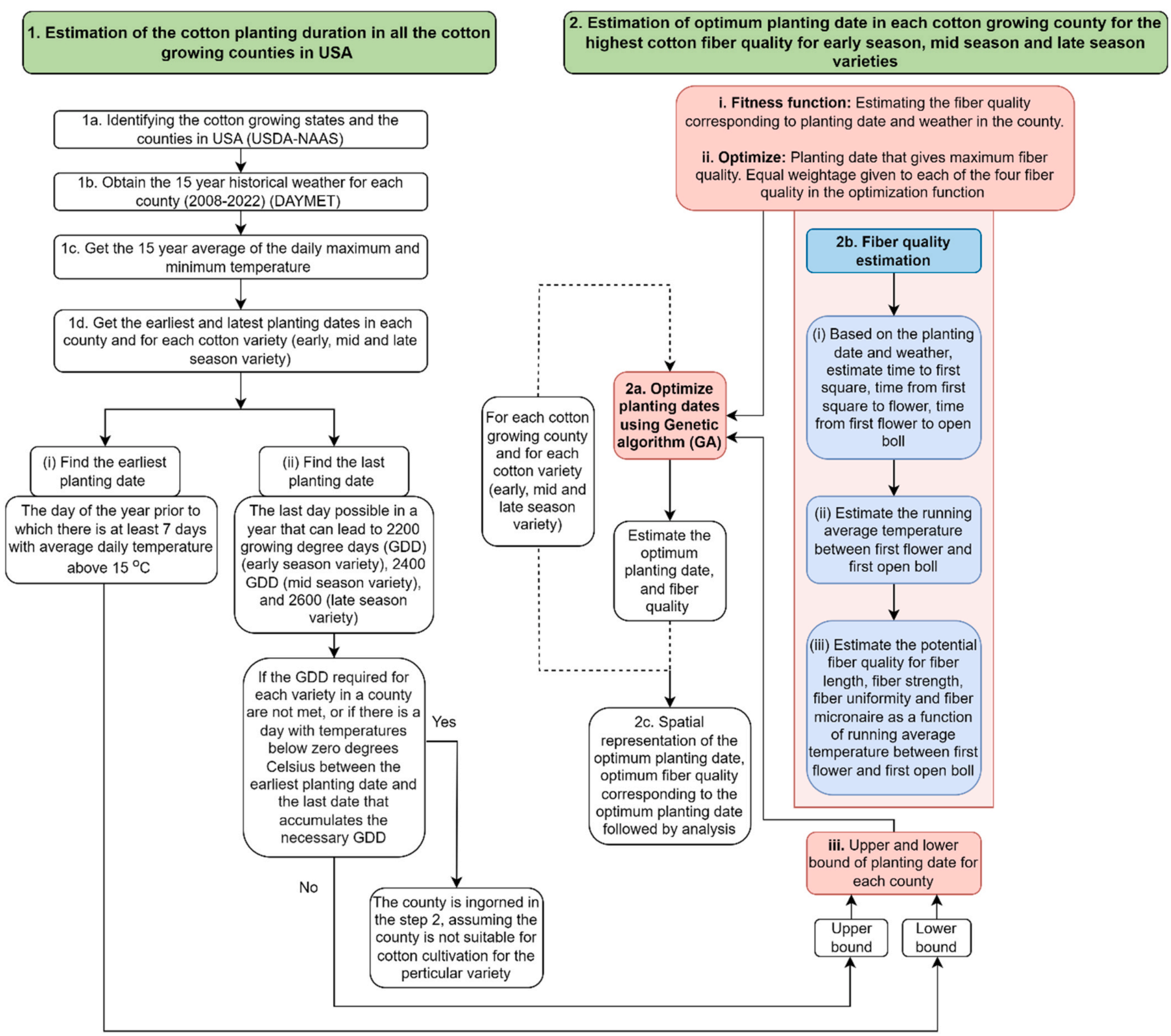

Fig. 1. The methodology adopted for estimating the optimum planting date for maximizing fiber quality. The two primary steps are presented in the green box, and all steps related to the genetic algorithm-based optimization are presented in light red boxes.

management practices, and environmental conditions impact cotton quality remains specific to particular cultivars, growing regions, or soil types. Comprehensive analyses on a larger scale, considering diverse weather conditions, have been relatively scarce. Moreover, there has been limited research on determining the optimal planting date to maximize fiber quality.

The study aims to determine the optimal planting date for enhancing fiber quality, considering cultivar characteristics and site-specific climatic conditions. The specific objectives are (a) to develop a methodology to optimize planting dates for maximizing fiber quality, (b) to illustrate the developed methodology, (c) to analyze the optimum planting date and the corresponding fiber quality achieved through the proposed methodology, (d) to apply the methodology under future climatic conditions to assess the variations in fiber quality and optimum planting dates, and (e) to discuss the applicability, limitations, and potential future developments of the developed methodology.

2. Materials and methods

Fig. 1 outlines the methodology for estimating the optimal planting date to maximize fiber quality in cotton-growing regions of the USA. Although the methodology is presented with a focus on the cotton-growing regions in the USA, it can be applied in any region. The major factors considered for estimating the optimum planting dates include planting dates, crop duration, temperature, Growing Degree Days (GDD), cotton variety (early-season, mid-season, late-season), and temperature-based functions for modeling the time from planting to the formation of the first square, the time from the first square to the first flower, and the time from the first flower to the first open boll. The methodology assumes that cotton receives sufficient water and nutrients, ensuring that fiber quality is not influenced by water or nutrient stress conditions.

There are two major steps involved in this methodology (marked in green boxes). The first step (**Step 1**) is to identify the planting duration in all cotton-growing counties. Planting duration refers to the earliest and last possible planting dates that support the growth of cotton. The second step (**Step 2**) is to identify the optimum planting date (represented as the day of the year) within the planting duration to maximize fiber quality using an optimization algorithm.

Step 1. Estimation of the cotton planting duration in all the cotton-growing counties in the USA

In this step, a list of cotton-growing counties in the USA was obtained, followed by acquiring 15 years of historical weather data for these counties. Estimates for the earliest and last planting dates were made based on each county's 15-year average weather conditions.

1. **Cotton-grown counties in the USA:** The list of states and counties in the USA where cotton has been grown over the past 15 years was obtained from the USDA-NASS (nass.usda.gov).
2. **15-Year historical weather data from cotton-growing counties:** Fifteen years of historical weather data, primarily consisting of maximum and minimum daily temperatures, were obtained for each county. The data was collected based on the centroid latitude and longitude of each county. R programming was utilized to determine the latitude and longitude of each county's centroid, employing the 'tigris' package (refer to the **data/source code availability section**). This weather data was sourced from the Daily Surface Weather and Climatological Summaries (DAYMET). DAYMET's single-pixel extraction tool enables the download of weather data in CSV tabular format for any specified latitude and longitude coordinates. Within the single-pixel extraction tool, the latitude and longitude coordinates were initially projected onto DAYMET's coordinate system. Subsequently, daily data from the nearest 1 km x 1 km DAYMET grid cell are extracted for further analysis. For access to the source code developed for weather data extraction, please see the **data/source code availability section**.
3. **Estimating the 15-year average of the maximum and minimum daily temperature:** After obtaining 15 years of weather data for each county, the 15-year daily average maximum and minimum temperatures for each county are estimated. These 15-year averages serve as the basis for further analysis in the proposed methodology. Instead of relying on data from a specific year, a 15-year average was chosen to represent the typical climate conditions in the cotton-grown counties in the USA, avoiding the potential influence of extreme weather conditions in any single year.
4. **Finding the earliest and last planting dates in each county**: The 15-year average of the temperature is utilized to determine the earliest and last planting days. These dates serve as the upper and lower limits for planting dates in the optimization algorithm (explained in **Step 2**).

i. **Earliest planting date:** To estimate the earliest planting date, the algorithm identifies the day before, which has at least seven consecutive days with an average daily temperature above 15°C. This criterion is in line with the requirements for cotton planting, which necessitate a minimum temperature of 15°C for successful germination. The temperature must consistently meet this criterion over seven consecutive days, as abrupt temperature fluctuations can impede the germination process and lead to poor stand establishment. The choice of seven days was based on recommendations from the literature regarding the required duration with temperatures above 15°C for optimal planting (Constable, 1976; Edmisten and Collins, 2023; Riley et al., 1964).

ii. **Last planting date:** The last possible planting date is estimated by accounting for the GDD requirements of early, mid-, and late-season cotton varieties. These cultivar groups are categorized based on their maturity and growing season characteristics. Early-season varieties have a shorter growing cycle and mature quickly, making them suitable for regions with short growing seasons. Mid-season varieties fall in between in terms of maturity and are well-suited for areas with average growing conditions, while late-season varieties have a longer growing cycle, requiring more time and warmth to mature, making them suitable for regions with extended growing seasons and warmer climates. The typical GDD requirements for early, mid, and late-season cultivars are 2200 GDD, 2400 GDD, and 2600 GDD, respectively (NCC, 2023; Wright et al., 2022).

The last planting date was estimated in such a way that the GDD requirement would be satisfied if the crop were planted on that last day. However, it's important to note that if there are not enough GDDs satisfied for each variety in a county or if there is a day with temperatures below zero °C between the planting date and the last day that accumulates the required GDD, then planting cotton may not be feasible for that specific county. Therefore, for each cultivar, the counties that do not satisfy these conditions were removed from the optimum planting date estimation, with the assumption that those counties are not suitable for cotton cultivation.

The source code developed for estimating the earliest planting date and finding the last planting dates for early, mid, and late-season cultivars is provided in the **data/model availability section**.

Step 2. Estimation of optimum planting date in each cotton growing county for the highest cotton fiber quality for early-season, mid-season, and late-season varieties

The earliest and last planting dates for each county were estimated in **Step 1**. The optimum/best planting date within these date ranges for maximizing fiber quality was determined in **Step 2**. The genetic algorithm optimization technique was employed as a quick and reliable method for estimating the optimum planting date (**Step 2a**).

Four major fiber quality indices (fiber length, fiber strength, micronaire, and uniformity) were calculated for each of the cultivars corresponding to different planting dates within the best earliest and last planting dates for each county and each cultivar. This calculation is based on the functional relationship between the running average temperature between cotton flowering and boll opening and the four major fiber quality indices (**Step 2b).** To achieve this, the time to the first square, time from the first square to the first flower, and time from the first flower to open boll are initially estimated for each planting date (**Step 2b (i)**). This provides the days between the flowering and boll opening stages. Within this interval, the running average temperature was computed for each county for different planting dates (**Step 2b (ii)**). Four fiber quality indices (fiber strength, length, micronaire, and uniformity) were then determined corresponding to the running average temperatures between flowering and open boll in each county and for each cultivar (**Step 2b (iii)**). This process was carried out for each possible planting date within the early and last planting date ranges estimated in **Step 1**. The planting date that results in the maximum fiber quality is reported as the optimum/best planting date. The process of finding the optimum planting date was simplified by adopting the genetic algorithm approach.

2.1. Optimize planting dates using the Genetic algorithm optimization technique

Genetic algorithm is a type of optimization algorithm that is inspired by the process of natural selection. It is used to find the optimal solution to a problem by mimicking the process of natural selection and evolution (McCall, 2005). The algorithm works by generating a population of candidate solutions, evaluating their fitness, and then selecting the best candidates to produce the next generation of solutions. This process is repeated until a satisfactory solution is found. The fitness function in the genetic algorithm is the function that the algorithm is trying to optimize. It is the function that defines the objective of the optimization problem. The limits of the genetic algorithm are determined by the number of maximum iterations and the population size. The maximum number of iterations determines how many generations of candidate solutions will be generated before the algorithm terminates. The population size determines how many candidate solutions are generated in each generation. The optimal values for these parameters depend on the specific problem being solved and can be determined through trial and error.

i. **Fitness function and optimization:** The fitness function in the genetic algorithm model is fiber quality. The fitness function component in genetic algorithm includes the estimation of time to the first square, time from the first square to flowering, and time from the first flower to open boll, followed by estimating the running average temperature between the first flower and open boll. This running average temperature was used for fiber quality estimation. The single value that was finally optimized was the equally weighted combination of the four fiber quality indices.
ii. **Upper and lower bounds:** In genetic algorithm-based optimization, the upper and lower bounds represent the minimum and maximum values that the variable being optimized can take during the optimization process. The earliest and last planting dates estimated in **Step 1** were used as the upper and lower bounds for optimizing the planting date variable using the genetic algorithm.

2.2. Fiber quality estimation

The first step in fiber quality estimation was the estimation of time to first square, time from first square to first flower, and from first flower to first open boll.

Time to the first square, time from first square to first flower, and from first flower to first open boll: The following are the functional relationships between temperature and time to the first square, first flower, and first open boll. These are based on the controlled experimental studies by Reddy et al. (1997a) (Reddy et al., 1997a).

Time to first square (T_{FS}) represents the time from emergence to the first square (days).

$$T_{FS} = (190.338 - 11.372 \quad \text{Avg}_{Temp,e} + 0.194 \quad \text{Avg}_{Temp,e}{}^2) \tag{1}$$

$\text{Avg}_{Temp,e}$ is the running average temperature from the emergence (°C).

Time from the first square to the first flower (T_{FF}) represents the time from the formation of the first square to the first flower (days).

$$T_{FF} = (252.591 - 15.321 \quad \text{Avg}_{Temp,s} + 0.2531 \quad \text{Avg}_{Temp,s}{}^2) \tag{2}$$

$\text{Avg}_{Temp,s}$ is the running average temperature of the squares (°C).

Eq. 3 gives the time from the first flower to the first open boll (T_{FO}) (days).

$$T_{FO} = (327.396 - 17.251 \quad \text{Avg}_{Temp,b} + 0.255 \quad \text{Avg}_{Temp,b}{}^2) \tag{3}$$

$\text{Avg}_{Temp,b}$ is the running average temperature of the cotton bolls (°C).

i. **Running average temperature between first flower and first open boll:** Once the T_{FF} and T_{FO} were estimated, the running averages of the daily temperature were calculated for the days between these two dates.
ii. **Fiber quality as a function of temperature:** Fiber quality estimation as a function of temperature was modeled based on the functions developed by Lokhande and Reddy in 2014 (Lokhande and Reddy, 2014). Lokhande & Reddy (2014) conducted soil-plant-atmosphere-research (SPAR) experiments to develop functional relationships between temperature and fiber quality (Lokhande and Reddy, 2014). The experiments were conducted for four day/night temperatures (22/14, 26/18, 30/22, and 34/26°C). Temperature controls were imposed from a few days before flowering to the maturity stage of the cotton crop grown at optimum temperature (30/22°C). All experiments were carried out at optimum water and nutrient availability. The fiber strength was observed to increase linearly with an increase in temperature. The micronaire and fiber uniformity increase with an increase in temperature up to 26°C and decline with a further rise in temperature. Fiber length increases with an increase in temperature up to 22°C and decreases at higher temperatures (Lokhande and Reddy, 2014). Supplementary Figure S1 shows the variation in the fiber quality indices, fiber strength (Figure S1a), fiber length (Figure S2b), micronaire (Figure S2c), and fiber uniformity (Figure S2d) with temperature based on the functional relationships in Eq. 4 (Beegum et al., 2023a). Eq. 4 shows the relationship between the fiber quality indices and temperature developed by Lokhande & Reddy (2014) (Lokhande and Reddy, 2014a).

$$\text{Fiber strength (g/tex)} = 21.817 + 0.341\ T$$

$$\text{Fiber length (mm)} = 11.5 + 1.75\ T - 0.04\ T^2$$

$$\text{Micronaire reading (-)} = -6.88 + 0.843\ T - 0.017\ T^2$$

$$\text{Fiber uniformity (\%)} = 55.04 + 2.37\ T - 0.047\ T^2 \tag{4}$$

T is the running average temperature (°C) between the first flower and open boll (estimated in Step 2b(ii))

2.3. Spatial representation and analysis

Once the genetic algorithm was executed for each county and each cotton variety, the optimum planting date and the fiber quality associated with the optimum planting date for each county corresponding to each variety were obtained. To facilitate the visualization of the observed results, spatial maps of these variables were generated.

3. Results

3.1. Cotton-growing states and counties

Based on the acres harvested and county-level yield data over the past 15 years, 17 states and a total of 765 counties were identified as cotton-growing regions (Fig. 2**a**, Supplementary Figure S2). This includes counties where cotton has grown in just one year in the last 15 years. The states that were identified as cotton-growing states are Alabama (AL), Arizona (AZ), Arkansas (AR), California (CA), Florida (FL), Georgia (GA), Kansas (KS), Louisiana (LA), Mississippi (MS), Missouri (MO), New Mexico (NM), North Carolina (NC), Oklahoma (OK), South Carolina (SC), Tennessee (TN), Texas (TX) and Virginia (VA). The three largest numbers of cotton-growing counties were found in Texas (177 counties), Georgia (98 counties), and Mississippi (66 counties). The three lowest cotton-grown counties were found in Arizona (10 counties), Missouri (14 counties), and New Mexico (14 counties) (Supplementary Figure S2). The total number of counties in each state and the total cotton planted area in each of the cotton-growing states in the USA is presented in Figures S3 and S4 **(Supplementary file),** respectively.

3.2. 15-year average, maximum, and minimum temperature

Figs. 2**b, **2**c, and **2**d** display the 15-year averages of the daily maximum, minimum, and average temperatures across all cotton-growing counties based on data obtained from DAYMET (**Steps 1b and 1c**). The temperature variations observed are similar to the annual average temperatures in the USA, as determined by NOAA's NCEI based on the 1991–2020 normals (refer to Supplementary Figure S5). The 15-year averages of the daily maximum, minimum, and average temperature in each state are presented in Supplementary Figure S6.

In general, the temperature is observed to decrease with an increase in latitude (Fig. 2). The highest and lowest 15-year average daily temperatures in the cotton-growing state were observed in Florida (20.5°C) and Kansas (13.4°C), respectively. The highest maximum daily average temperature was in Florida (26.6°C), and the lowest was in Missouri (19.6°C). The top three states with the highest maximum daily average temperatures in cotton-growing counties were Florida (26.6°C), Arizona (26.5°C), and Texas (25.6°C). The lowest maximum average temperatures were observed in Missouri (19.62°C), Virginia (20.5°C), and Kansas (20.8°C). The top three states with the highest minimum temperatures in cotton-growing counties were Florida (14.4°C), Louisiana (13.2°C), and Georgia (12.2°C). The lowest minimum average temperatures were observed in Kansas (6.0°C), New Mexico (6.01°C), and

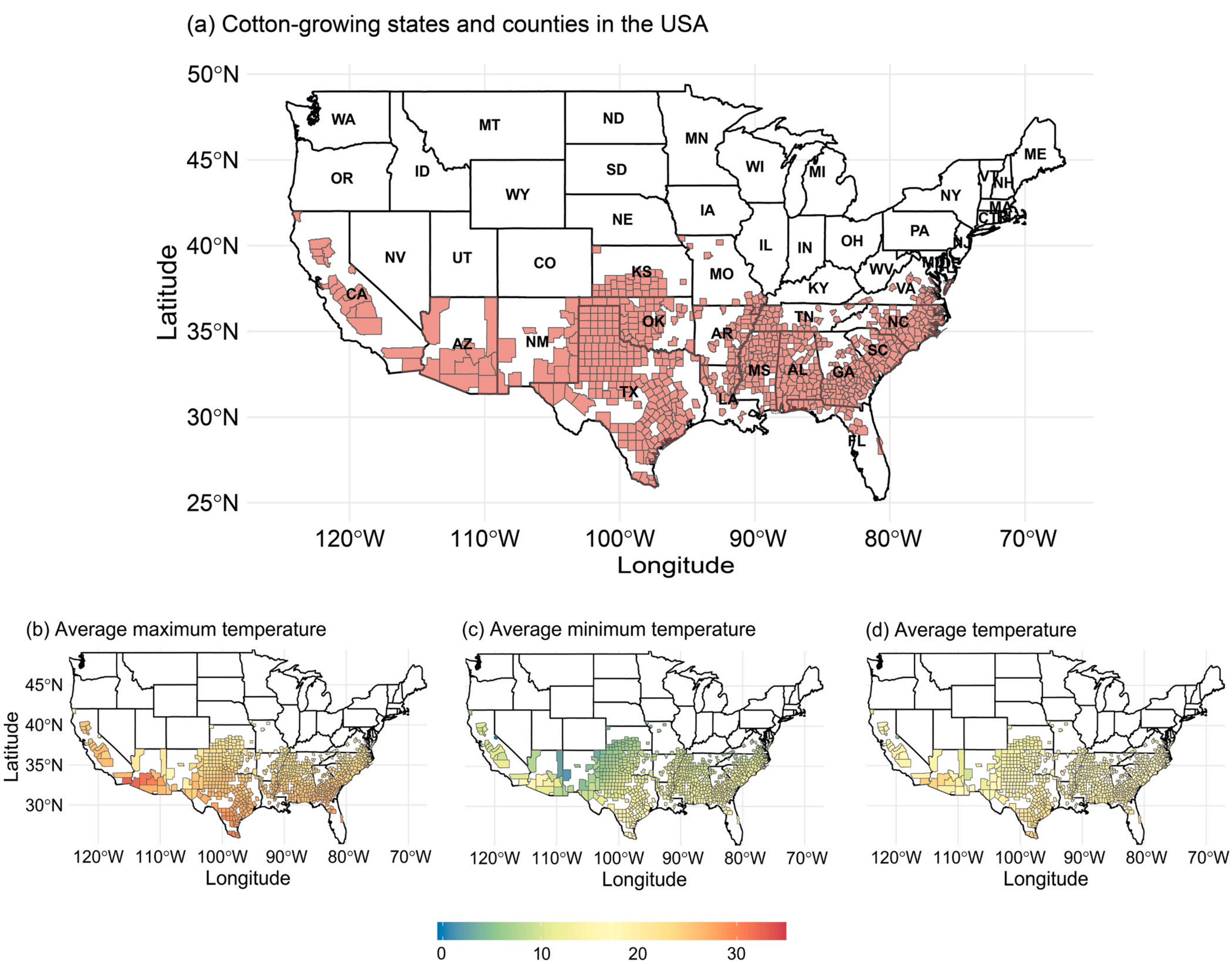

Fig. 2. (a) Cotton-grown states (17 states) and counties (765 counties) in the USA, (b) 15-year average of the daily maximum, (c) daily minimum, and (d) daily temperatures (°C) in the counties where cotton is grown in the USA. The cotton-growing states are Alabama (AL), Arizona (AZ), Arkansas (AR), California (CA), Florida (FL), Georgia (GA), Kansas (KS), Louisiana (LA), Mississippi (MS), Missouri (MO), New Mexico (NM), North Carolina (NC), Oklahoma (OK), South Carolina (SC), Tennessee (TN), Texas (TX) and Virginia (VA).

Missouri (7.9°C) (see Supplementary Figure S2).

3.3. Earliest and last planting dates and planting interval

The earliest and last planting dates are estimated based on the method discussed in **Step 1d** (Fig. 1). Fig. 3 shows the earliest and latest planting dates for late (Figs. 3**a and** 3**b**), mid (Figs. 3**c and** 3**d**), and early-season (Figs. 3**e and** 3**f**) varieties, as well as the number of counties suitable for each variety. When estimating the earliest and latest planting dates, it was found that some counties are not suitable for specific varieties, meaning there are not enough days to satisfy the GDD required for each variety. For example, for late-season varieties, the GDD requirement is 2600 GDD. Among the total number of counties where cotton has been grown in the last 15 years, only 527 are suitable for late-season varieties. This means that only these 527 counties satisfy the minimum temperature requirement at planting and the cumulative

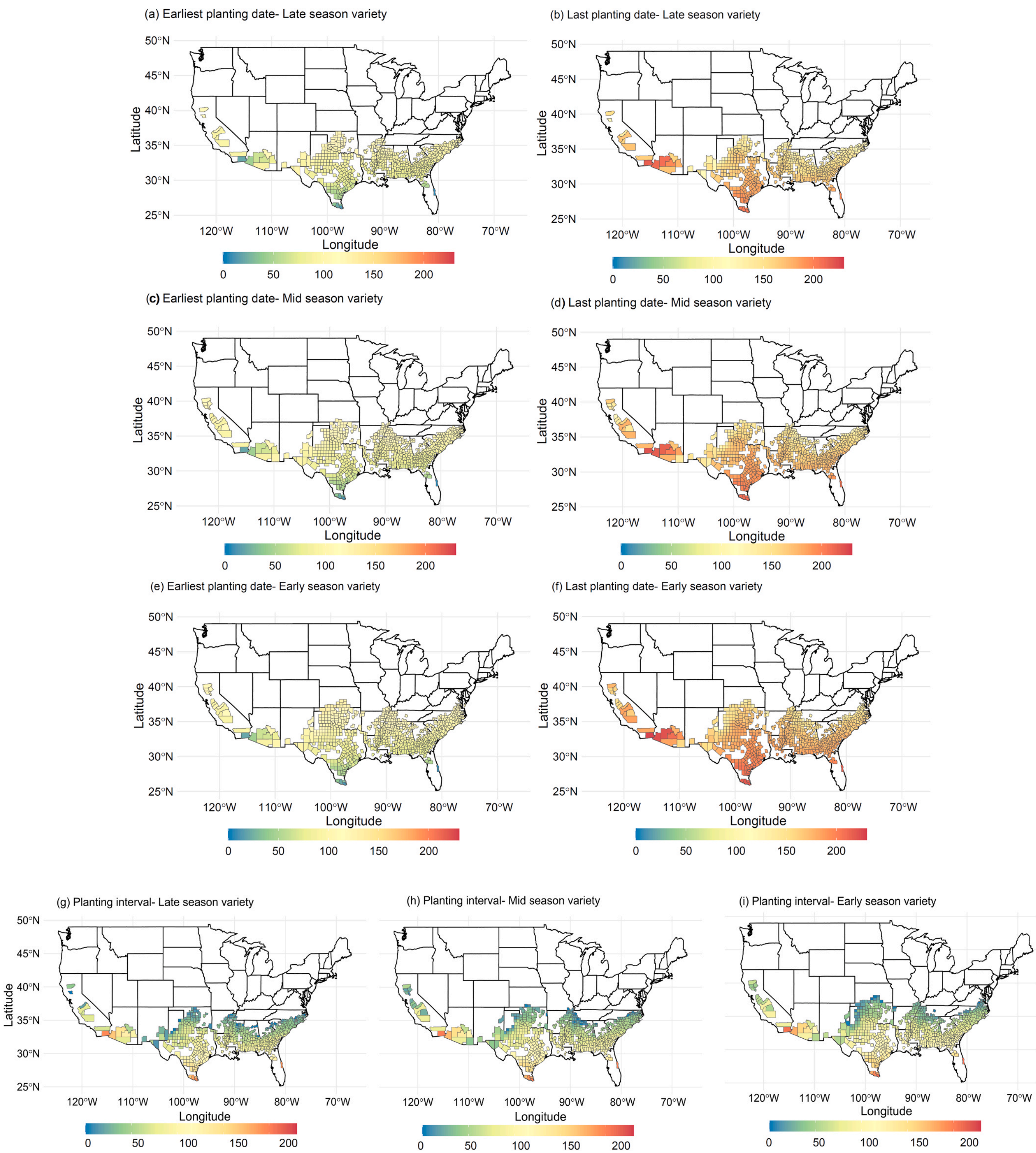

Fig. 3. (a, c, e) Earliest and (b, d, f) last planting dates (day of the year) for each of the cotton varieties: (a, b) late-season, (c, d) mid-season, and (e, f) early-season varieties) and planting interval (days) for (g) late-season, (h) mid-season, and (i) early-season varieties at the county level.

GDD of 2600. If late-season varieties are grown in other counties, the cotton crop will not be able to accumulate the necessary GDD for their growth. Similarly, for mid and early-season varieties, the total number of counties where cotton can be grown is 615 and 685, respectively (Fig. 3).

Late-season varieties require more GDD compared to mid and early-season varieties. The number of counties suitable for late-season cultivation tends to decrease, especially in the northern states/counties. For example, no counties were suitable for late-season varieties in Kansas, while two counties were suitable for mid-season varieties, and 13 counties were suitable for early-season varieties. A similar observation was made in Missouri, with zero counties suitable for late-season varieties and 3 and 6 for mid and early-season varieties, respectively (Fig. 3).

For late, mid, and early-season varieties, the earliest planting dates increase, and the latest planting dates decrease with an increase in latitude. This variation aligns with the spatial variability in temperature and the GDD requirement for each variety. Spatial variability in temperature shows a decrease in temperature with an increase in latitude (Fig. 2**d**, **Section 3.2**), which delays the earliest planting date in the northern counties. This also results in a decrease in the latest planting date in the northern region compared to the south. The planting interval for late, mid, and early-season varieties is presented in Fig. 3 **g, h, and i**, respectively. The most prolonged planting intervals were found in the counties in the southern USA, and the planting interval decreased as one moved to the northern counties. This is due to the delay in the earliest planting time and the decrease in the latest planting time with an increase in latitude. The longest planting intervals are observed in counties in Texas, Florida, California, and Arizona.

3.4. Optimum planting dates and fiber quality

The optimum planting date that maximizes fiber quality was estimated, as discussed in **Step 2** (Fig. 1), and is presented in Figs. 4**a to** 4**c**. The optimum planting date ranged from 18.5 to 211 days, 27.8–212 days, and 8.0–212.2 days for early, mid, and late-season varieties. These optimum planting dates are based on the available planting interval for each cotton variety and the temperature between the flowering and open boll.

For late-season varieties, earlier planting compared to mid and early-season varieties leads to higher fiber quality (Fig. 4**a**). For the late-season varieties, in general, the optimum planting date increased with an increase in latitude. For early-season varieties, a delay in planting led to higher fiber quality compared to late and mid-season varieties (Fig. 4**c**). A more delayed planting date in New Mexico and southern counties of Texas, compared to other counties, led to higher fiber quality in the early-season varieties (Fig. 4**c**). When comparing the early, mid, and late-season varieties, in general, a more delayed planting for early and mid-season varieties compared to late-season varieties resulted in higher fiber quality (Figs. 4**a,** 4**b, and** 4**c**)

The fiber quality at optimum planting date at the county level for early, mid, and late-season varieties are presented in Fig. 4**g to 4o**. The ranges of fiber length, strength, micronaire, uniformity, optimum planting date, and average temperature are given in Table 1. Interpretations of the fiber quality ranges are also provided, referencing the standard quality scale presented in Supplementary Table S1. Fiber length values range from medium to long and strength from strong to very strong. Micronaire values span from the discount range to the base range, and uniformity falls into the class high for all the cultivars.

For fiber length, when planting at the optimum planting date, the early-season varieties resulted in higher fiber quality (median value for all the counties is 29.8 mm) compared to mid (29.5 mm) and late-season varieties (29.3 mm) (Figs. 4**d,** 4**e, and** 4**f**). For strength, the late-season variety showed higher strength (31.1 g/tex, Fig. 4**g**) compared to mid-season (31.0 g/tex) and early-season varieties (30.7 g tex-1). Micronaire was higher for the early-season variety (3.52, Fig. 4**l**) compared to the mid (3.47, Fig. 4**k**) and late-season variety (3.44, Fig. 4**j**). Similarly, uniformity was also higher for the early-season variety (84.8 %, Fig. 4**o**) compared to the mid (84.7 %, Fig. 4**n**) and late-season variety (84.6 %, Fig. 4**m**).

In general, the length, micronaire, and uniformity were higher for the early-season variety compared to mid and late-season varieties, whereas strength was higher for the late-season variety compared to mid and early-season varieties when planted at the optimum planting date (Figs. 4**d to** 4**o**). More details on the spatial variability of the optimum planting date and fiber quality are discussed in **Section 3.5** **.**

3.5. Variation in the optimum fiber quality and planting date for current and future weather scenarios

Section 3.4 is based on weather data from the last 15 years. This section discusses the variations in planting dates and fiber quality in relation to future weather conditions and compares them with variations in planting dates and fiber quality based on the last 15 years of weather conditions. Multiple temperature scenarios from the IPCC's AR6 2021 Climate Report were employed to analyze future weather conditions (Arias et al., 2021). This report summarizes five different possible temperature scenarios. Scenario 1: Most optimistic (+1.5°C by 2050, SSP1–1.9), Scenario 2: Next best (1.8°C by 2100, SSP1–2.6), Scenario 3: Middle of the road: 2.7°C by 2100, SSP2–4.5) Scenario 4: Dangerous (3.6°C by 2100, SSP3–7.0), Scenario 5: Avoid at all costs (4.4°C by 2100, SSP5–8.5). The optimum planting date and fiber quality variability are analyzed for these five future weather scenarios, along with the weather scenario based on the average weather conditions in the last 15 years for each of the three cultivars. The total number of scenarios includes 18 (3 cotton varieties * 6 climatic variations (15-year average weather, 15-year average weather + 1.5°C, 15-year average weather + 1.8°C, 15-year average weather + 2.7°C, 15-year average weather + 3.6°C, 15-year average weather + 4.4°C). The list is presented in Table 2**.**

When comparing simulated results based on the proposed methodology, considerable variations were observed in the counties favorable for cotton cultivation, optimum planting dates, optimized fiber quality, time to square, flower, and open boll, as well as the running average temperature between the time to flower and open boll. Each of these factors is discussed in the following sections.

3.5.1. Percentage variation in the counties favorable for cotton cultivation

The number of counties capable of growing cotton increased with higher temperature scenarios for all three cotton varieties (Supplementary Figure S7). For early-season varieties, the total number of cotton-growing counties increased from 685 (considering the 15-year average temperature condition) to 761 (15-year average weather + 4.4°C). For mid-season varieties, the total number of counties increased from 614 to 760 counties; for late-season varieties, it increased from 527 to 756 counties. The increase in the number of counties with an increase in temperature is due to higher temperatures contributing more towards the GDD within a shorter period compared to lower temperatures. The additional counties are primarily located in the northern regions of the cotton belt. In general, temperatures decrease with an increase in latitude (Fig. 2); therefore, an increase in temperature is more advantageous for the counties at higher latitudes. The highest number of counties for cotton cultivation was observed for early-season varieties in the scenario with 15-year average weather + 4.4°C, while the minimum was observed for late-season varieties under 15-year average weather conditions (Supplementary Figure S7)

3.5.2. Variation in the time to the first square, flower, and open boll

Based on several experimental studies carried out on the impact of temperature on time to the first square, flower, and open boll, it has been observed that the time to these reproductive stages is highly dependent on temperature. For the time to square, the base temperature at which no progress occurred toward square formation was 15°C (Reddy et al., 1997a). The maximum rate of progress was around 30°C, followed by a

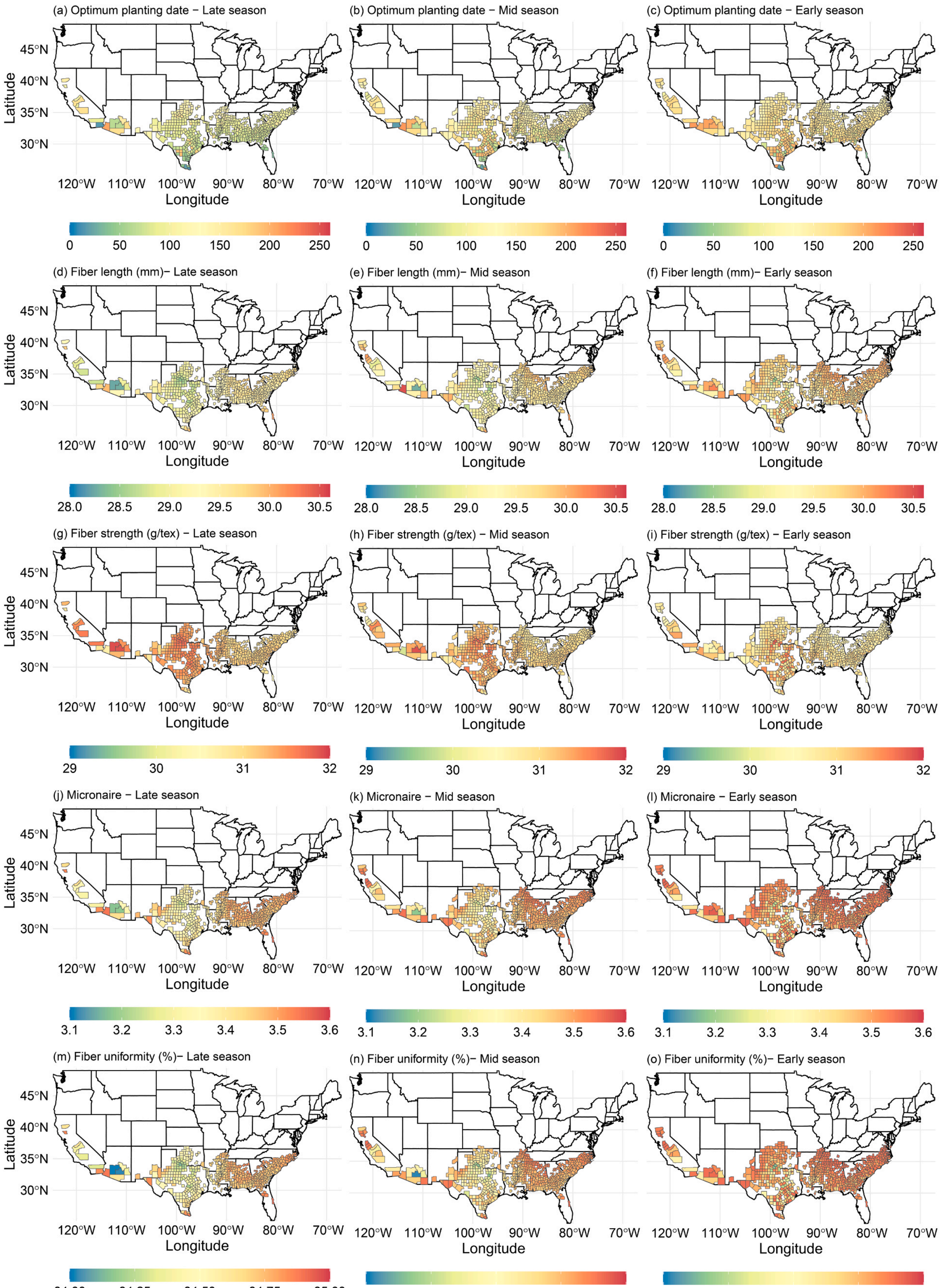

Fig. 4. (a, b, c) Optimum planting date (day of the year) and the (d, e, f) fiber length, (g, h, i) fiber strength, (j, k, l) micronaire, and (m, n, o) uniformity corresponding to the optimum planting date for the late, mid and early-season varieties.

Table 1
The range of the optimum planting dates (day of the year), running average temperatures, and fiber quality indices (fiber length, strength, micronaire, uniformity) among early-season, mid-season, and late-season cotton varieties.

	Late-season variety	Mid-season variety	Early-season variety	Interpretation of the fiber quality*
Fiber length (mm)	27.9 – 30.1	28.4 – 30.1	28.4–30.2	Medium to long
Fiber strength (g/tex)	30.5 – 32.0	30.4 – 31.7	30.3–31.7	Strong to very strong
Micronaire (-)	3.1 – 3.5	3.2 – 3.5	3.2–3.5	Discount range to base range
Uniformity (%)	83.8 – 84.9	84.1 – 84.9	84.1–84.9	High
Planting date (day of the year)	8.0 – 212.2	27.8 – 212	18.5 – 211.0	
Running average temperature (°C)	25.4 – 30.0	25.4 – 29.2	25.0 – 29.2	

* Refer to Supplementary Table S1 for the interpretation of the cotton fiber quality indices.

Table 2
Climate change scenarios analyzed for the variation in the fiber quality and optimum planting date for different cotton varieties (early, mid, and late season varieties). The climate change scenarios are based on the future scenarios from the IPCC's AR6 2021 Climate Report (Arias et al., 2021).

Variety	Notation	Description of the scenario
Early season	15-year avg.	This represents the 15-year average temperature.
	15-year avg. + 1.5°C	This represents 15-year avg.+ 1.5°C: Most optimistic (+1.5°C by 2050, SSP1–1.9)
	15-year avg. + 1.8°C	This represents 15-year avg.+ 1.8°C: Next best (+1.8°C by 2100, SSP1–2.6)
	15-year avg. + 2.7°C	This represents 15-year avg.+ 2.7°C: Middle of the road (+2.7°C by 2100, SSP2–4.5)
	15-year avg. + 3.6°C	This represents 15-year avg.+ 3.6°C: Dangerous (+3.6°C by 2100, SSP3–7.0)
	15-year avg. + 4.4°C	This represents 15-year avg.+ 4.4°C: Avoid at all costs (+4.4°C by 2100, SSP5–8.5)
Mid-season	15-year avg.	This represents the 15-year average temperature.
	15-year avg. + 1.5°C	This represents 15-year avg.+ 1.5°C: Most optimistic (+1.5°C by 2050, SSP1–1.9)
	15-year avg. + 1.8°C	This represents 15-year avg.+ 1.8°C: Next best (+1.8°C by 2100, SSP1–2.6)
	15-year avg. + 2.7°C	This represents 15-year avg.+ 2.7°C: Middle of the road (+2.7°C by 2100, SSP2–4.5)
	15-year avg. + 3.6°C	This represents 15-year avg.+ 3.6°C: Dangerous (+3.6°C by 2100, SSP3–7.0)
	15-year avg. + 4.4°C	This represents 15-year avg.+ 4.4°C: Avoid at all costs (+4.4°C by 2100, SSP5–8.5)
Late season	15-year avg.	This represents the 15-year average temperature.
	15-year avg. + 1.5°C	This represents 15-year avg.+ 1.5°C: Most optimistic (+1.5°C by 2050, SSP1–1.9)
	15-year avg. + 1.8°C	This represents 15-year avg.+ 1.8°C: Next best (+1.8°C by 2100, SSP1–2.6)
	15-year avg. + 2.7°C	This represents 15-year avg.+ 2.7°C: Middle of the road (+2.7 °C by 2100, SSP2–4.5)
	15-year avg. + 3.6°C	This represents 15-year avg.+ 3.6°C: Dangerous (+3.6°C by 2100, SSP3–7.0)
	15-year avg. + 4.4°C	This represents 15-year avg.+ 4.4°C: Avoid at all costs (+4.4°C by 2100, SSP5–8.5)

decrease in the rate with temperatures above 30°C. The maximum rate of progress from squaring to flowering increased up to a temperature of 27°C, followed by a decrease in the rate. The rate of progress from flowering to open boll did not show a slowing at temperatures above 30°C compared to the rate of progress toward squaring and flowering. This is represented in the functions (Eqs. 1 to 3) used in the methodology of this study (**Section 2.1**) (Reddy et al., 1997a).

A corresponding variation in the time to the first square, flower, and open boll was observed with variations in the temperature conditions under all 18 scenarios (Table 2). Among these events, the most important was the time from flower to open boll since the average temperature between the flower and open boll affects the fiber quality the most.

Fig. 5**a and b** show the variation in the running average temperature and number of days from flower to open boll in all 18 scenarios and for each state where cotton is grown. The values plotted are the median of all the times from flower to open boll in all the counties in each state. The median value is plotted since cotton is not equally grown in all counties of the states, and a mean value may not represent the general trend.

The running average temperature between the first flower and the first open boll increased with an increase in temperature (Fig. 5**a**). The running average temperature for each cultivar increased in the order of early, mid, and late-season varieties. For the early-season variety, the running average temperature increased from 26.3°C (15-year avg.) to 30.7°C (15-year avg. + 4.4°C). For the mid and late-season varieties, it increased from 27.0°C (15-year avg.) to 31.2°C (15-year avg. + 4.4°C) and from 27.5°C (15-year avg.) to 31.5°C (15-year avg. + 4.4°C) respectively (Fig. 5**a**).

Days from flower to open boll decreased with an increase in temperature (Fig. 5**b**). Similar findings are reported in several studies (Davidonis et al., 2004; Reddy et al., 1997b). Though there is an overall average trend among all the states, there are some states and counties that vary from the average of all the states. For instance, for all varieties and for the future scenario (15-year avg. + 1.8°C to 15-year avg. + 4.4°C), there is an increase in the time from flower to open boll for the states of California and Florida (Fig. 5**b**). This is due to the earlier optimum planting day for these two states, requiring more time for the bolls to open. Similarly, for the running average temperature between the flower and open boll stages, the states of California, Florida, and Georgia have comparatively low temperatures, whereas Arkansas and Kansas have relatively high temperatures. Discussing the variation in the days from first flower to open boll, as well as the running average temperature from flowering to open boll, at the state level is complex. This complexity is due to the fact that some states stretch across the entire latitude range where cotton is typically cultivated, making it challenging to accurately capture temperature variations along the latitude (Fig. 2**a**). Additionally, the values reported for each state represent median values, which may not fully convey the range or distribution of conditions within each state.

3.5.3. Variation in the planting date

The different temperature scenarios have greatly influenced the optimum planting date for higher fiber quality (Fig. 5**c**). The optimum planting dates for the early-season variety are later (158 days) compared to the mid-season varieties (116 days) and late-season varieties (91 days). The optimum planting date shifts earlier with an increase in temperature for each variety. Planting early-season varieties later in the season allows for more suitable temperatures, leading to improved fiber quality (Fig. 5**c**).

3.5.4. Variations in the fiber quality

For all varieties, fiber uniformity, length, and micronaire declined with an increase in temperature (from the 15-year average to the 15-year average + 4.4°C, Table 2), while strength increased with higher temperatures (Fig. 6). Length decreased from 29.8 mm to 27.44 mm for early-season varieties, from 29.55 mm to 27.07 mm for mid-season varieties, and from 29.36 mm to 26.88 mm for late-season varieties with an increase in temperature (Fig. 6**a**).

The fiber strength increased from 30.79 g/tex to 32.30 g/tex for

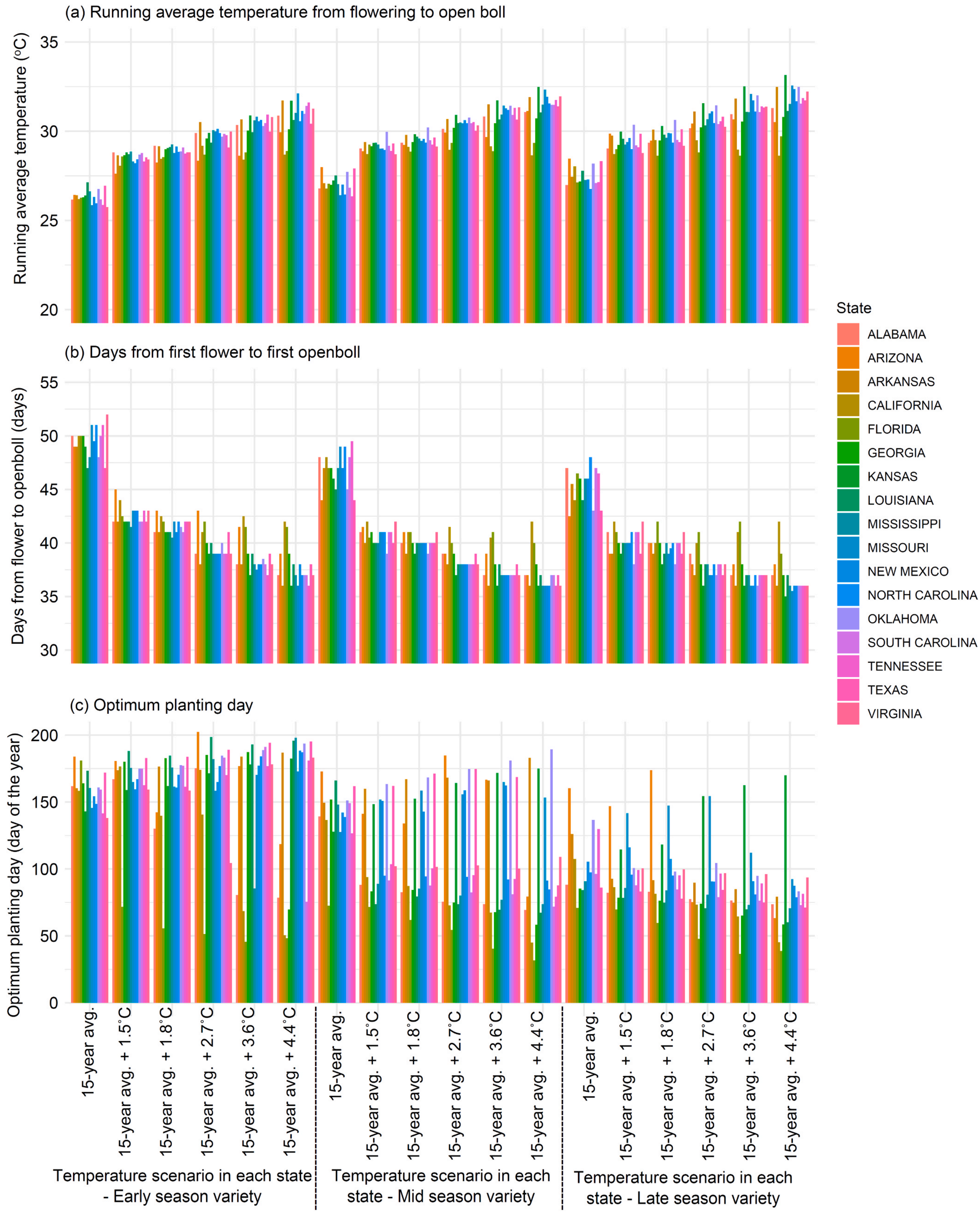

Fig. 5. The median value of (a) running average temperature from flowering to open boll, (b) days from first flower to open boll, and (c) optimum planting date (day of the year) for each of the states where cotton is grown, for early, mid, and late season varieties under different temperature scenarios (15-year avg., 15-year avg. + 1.5°C, 15-year avg. + 1.8°C, 15-year avg. + 2.7°C, 15-year avg. + 3.6°C, 15-year avg. + 4.4°C; Table 2).

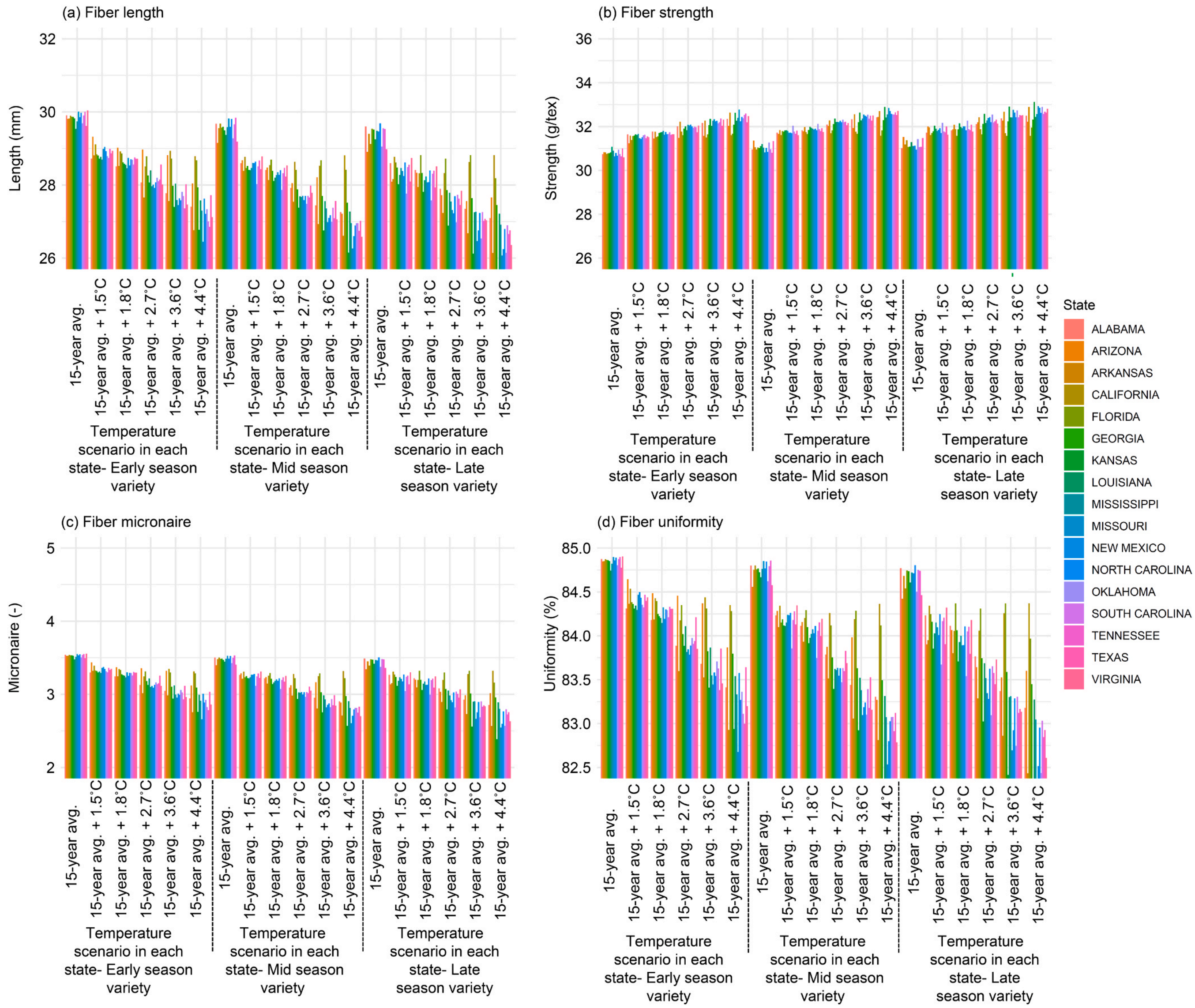

Fig. 6. Cotton fiber quality: (a) fiber length, (b) fiber strength, (c) micronaire, (d) uniformity at different temperature scenarios for early, mid, and late-season varieties. The values are the median for each state. Refer to Table 2 for the temperature scenarios (15-year avg., 15-year avg. + 1.5°C, 15-year avg. + 1.8°C, 15-year avg. + 2.7°C, 15-year avg. + 3.6°C, 15-year avg. + 4.4°C) shown on the x-axis.

early-season varieties, from 31.04 g/tex to 32.48 g/tex for mid-season varieties, and from 31.1 g/tex to 32.56 g/tex for late-season varieties (Fig. 6**b**). Micronaire values decreased from 3.52 to 2.95 for early-season varieties, from 3.47 to 2.84 for mid-season varieties, and from 3.44 to 2.78 for late-season varieties with an increase in temperature (Fig. 6**c**). Uniformity decreased from an average of 84.85–83.42 % for early-season varieties, from 84.7 % to 83.14 % for mid-season varieties, and from 84.65 % to 82.9 % for late-season varieties with an increase in temperature (Fig. 6**d**). The highest fiber length, micronaire, and uniformity were observed in early-season varieties, followed by mid- and late-season varieties (Figs. 6**a**, 6**c, and** 6**d**).

The percentage reduction in fiber length, micronaire, and uniformity with temperature was highest for the late-season variety compared to the mid and early-season varieties (Fig. 6). The percentage reduction in fiber length with an increase in temperature was 8.4 %, 8.3 %, and 8.0 % for late, mid, and early-season varieties, respectively (Fig. 6**a**). For fiber micronaire, the percentage reduction was 19.0 %, 18.3 %, and 16.3 % for late, mid, and early-season varieties, respectively (Fig. 6**c**). A percentage decrease of 1.9 %, 1.8 %, and 1.6 % was observed for fiber uniformity with an increase in temperature for late, mid, and early-season varieties, respectively (Fig. 6**d**). Among all the fiber quality indices, micronaire showed the maximum reduction in quality (19 %, late-season variety), and uniformity showed the minimum reduction (1.6 %, early-season variety) in quality with an increase in temperature (Fig. 6).

The fiber quality variation was analyzed based on the fiber quality class (e.g., strength: very strong, strong, average, intermediate, weak; refer to Supplementary Table S1). The number of counties that fall into each of the fiber quality classes was calculated for each of the temperature scenarios (6 scenarios), varieties (3 varieties), as well as for the four fiber quality indices and 16 fiber quality classes (4 classes for fiber strength, three classes for length, three classes for micronaire, five classes for fiber uniformity; refer to Supplementary Table S1) (Fig. 7).

For fiber length, the number of counties with long fiber decreased in the following order: early (104 counties), mid (8 counties), and late-season (1 county) varieties, based on simulations using the last 15-year weather scenario (15-year avg.) (Fig. 7**a**). In the scenario with an average temperature plus 4.4°C (15-year avg. + 4.4°C), the number of counties with short fiber increased in the order of early (5 counties), mid (11 counties), and late-season (19 counties) varieties. The number of

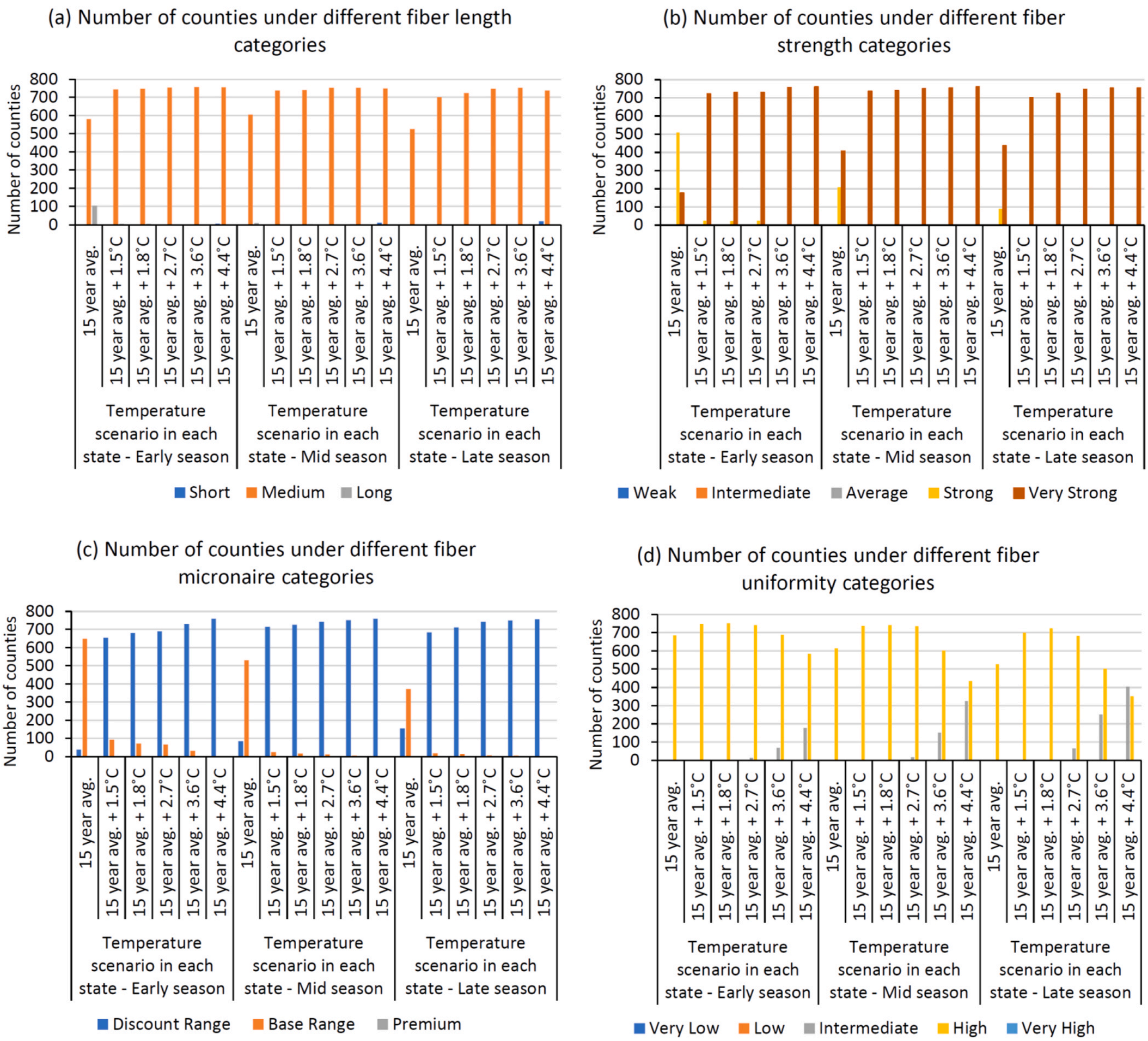

Fig. 7. The number of counties under different quality categories (refer to Supplementary Table S1) for (a) fiber length (short, medium, and long), (b) fiber strength (weak, intermediate, average, strong, and very strong), (c) fiber micronaire (discount range, base range, and premium), and (d) uniformity (very low, low, intermediate, high, and very high) for early, mid, and late season varieties and different temperature scenarios (15-year avg., 15-year avg. + 1.5°C, 15-year avg. + 1.8°C, 15-year avg. + 2.7°C, 15-year avg. + 3.6°C, 15-year avg. + 4.4°C; Table 2).

counties with medium fiber length first increased and then decreased in all the varieties with an increase in temperature (Fig. 7**a**). A decrease in fiber length was also reported in other studies. Meredith et al. (2005) observed a 6 % decrease in staple length when the temperature increased from 30.8 to 35.2°C (Meredith Jr, 2005). Reddy et al. (1999) also observed a decrease in fiber length from 30 to 27 mm with an average temperature increase from 17 to 32°C (Reddy et al., 1999).

Regarding fiber strength, the number of counties exhibiting very strong fiber quality rose, while strong quality decreased with temperature in the order of early, mid, and late-season varieties. An overall increase in fiber strength was observed with an increase in temperature (Fig. 7**b**). For micronaire, the counties with base range quality decreased with a rise in temperature for all varieties. The count decreased from 648 to 3 counties for early-season varieties, from 530 to 2 for mid-season varieties, and from 372 to 1 for late-season varieties (Fig. 7**c**). The micronaire quality with discount range increased with an increase in temperature for all varieties. The number of counties with discount range quality increased from 37 to 758 for early-season varieties, from 84 to 758 for mid-season varieties, and from 155 to 755 for late-season varieties (Fig. 7**c**)

For fiber uniformity, the number of counties with intermediate quality increased with an increase in temperature in the order of early, mid, and late-season varieties (Fig. 7**d**). For instance, for temperature conditions with 4.4°C higher than the 15-year average, the number increased from 178 (early season) to 325 (mid-season) to 405 (late-season varieties). At the same time, for the same scenario (15-year avg. + 4.4°C), the number of counties with a high level of fiber uniformity decreased from 583 (early season) to 435 (mid-season) to 351 (late-season varieties) (Fig. 7**d**). The number of counties with high fiber quality is higher for the early-season variety for all the temperature ranges. Within each variety, the number of states with high fiber quality increased with an increase in temperature followed by a decrease

(Fig. 7**d**).

4. Discussion

The National Oceanic and Atmospheric Administration's (NOAA) 2023 annual report shows that global temperature has increased at an average rate of 0.06°C per decade since 1850. The rate of warming since 1982 is more than three times as fast: 0.20°C per decade (Lindsey and Dahlman, 2024). The cotton crop is highly dependent on temperature conditions, and studies have shown both positive and negative impacts on cotton with increases in temperature (Jans et al., 2021; Liakatas et al., 1998). Each of the growth stages (time to square, flowering, boll opening, etc.) and fiber quality indices respond differently to an increase in temperature. Days to first square decrease from 61 days at 18°C to 30 days at 30°C, followed by a more gradual decrease with increases in temperature above 30°C. The time from square to flower decreases from 65 days at 15°C to 29 days at 30°C, followed by an increase when temperature increases beyond 30°C. The days from flowering to boll opening show a decreasing trend with an increase in temperature (Reddy, 1994). For the fiber quality indices, micronaire and uniformity were found to increase up to 26°C and decline with higher temperatures, whereas length increased up to 22°C followed by a decrease. Strength is observed to increase with an increase in temperature. Fiber micronaire was the most responsive to changes in temperature (Lokhande and Reddy, 2014a, 2014b). Due to the differential impact of temperate on different aspects of cotton, defining optimal temperature conditions for cotton is challenging (Burke and Wanjura, 2010).

Modeling the impact of temperature on fiber quality needs to account for the interactive variations in growth stages and fiber quality with temperature. The foundation of the methodology adopted in this study is the temperature-based functional equations that estimate critical growth stages—time to square, flowering, and boll opening—and fiber quality. These equations are derived from experimental studies focused on the growth, development, and quality aspects of the cotton crop under varying temperature conditions ranging from 22/14°C to 34/26°C (day/night temperature) (Lokhande and Reddy, 2014a; Reddy, 1994).

The developed methodology is demonstrated across the United States, covering all counties where cotton has been grown in the last 15 years. While the USDA-NASS provides records of acres harvested and county-level yield data in the US, this is the first study to analyze the total number of counties where cotton is grown based on this database, analyzing temperature, planting date, and fiber quality variation at the county level in the entire cotton belt.

The observed average, maximum, and minimum temperature variability across the counties aligns with other studies highlighting spatial temperature variability in the cotton belt (Liang et al., 2012). Spatial temperature maps for the cotton-growing counties depict the range of temperatures favorable to cotton cultivation and the predominance of cotton cultivation in the southern states of the US. The cotton-growing states and counties are primarily influenced by the climate, characterized by long growing seasons with high temperatures and relatively mild winters (Kincer, 1922). Additionally, the months during which the crop matures and is harvested are typically dry in the cotton belt (Jones and Durand, 1954).

The methodology for estimating the earliest and latest planting dates considers the effect of lower temperatures that can inhibit seed germination and the total GDD requirements for different cotton varieties, which are the two critical factors for cotton planting. The approach for determining the planting interval and the optimal planting date for maximizing fiber quality has reasonably simulated these factors. The analysis of the planting interval in the study concluded that the planting interval increased with a decrease in latitude, which aligns with the results of the literature. For example, the prolonged planting intervals in the southern states/counties are reported in studies by Davidonis et al. (2004) and Porter et al. (1996) (Davidonis et al., 2004; Porter et al., 1996). The limited growing season for cotton in Kansas, which is one of the states in the north of the cotton belt, is reported by Baumhardt et al. (2021) (Baumhardt et al., 2021). Peabody et al. (2002) discussed how the freezing temperatures in late spring and early fall in the northern High Plains region of Texas require planting in late May to ensure maturation before mid-October. Peabody et al. (2002) observed that planting an early-season variety later can result in higher fiber quality (Peabody et al., 2002). A similar observation is made in the present study.

The methodology effectively identified counties unsuitable for growing certain varieties, further demonstrating its reliability. For example, short-season varieties with a low GDD requirement are found to be more suitable in the northern counties than in the mid and late-season varieties. The methodology captures temperature variability at the county level and correlate it with the temperature requirement of the cultivar in relation to the planting date.

Furthermore, the methodology is applied to analyze the impact of future climatic variability on optimum planting dates and fiber quality, providing insights into potential future considerations for cotton cultivation. From the present study, the increase in temperature in future climatic conditions has led to earlier optimum planting dates for all cotton varieties. This is due to the shift in the earliest possible planting date, estimated based on the minimum temperature requirement for seed emergence, which decreases with an increase in temperature. Observations from future climate analyses have noted a decrease in fiber length, micronaire, and uniformity and an increase in strength with the increase in temperature conditions. Similar observations were made by Reddy et al. (1999), where it was observed that fibers were longer when bolls grew at temperatures lower than optimal (25°C). An increase in fiber strength with an increase in the future temperature conditions observed in the current study is similar to observations made by Pettigrew, (2008).

The methodology from this study offers valuable insights for identifying the suitability of different cotton varieties in various locations, along with optimum planting dates, enabling farmers to make informed choices and avoid potential losses. The future weather condition analysis can assist producers and farmers in anticipating changes in growing conditions and adjusting planting dates to adapt their farming practices accordingly. Understanding how future climate scenarios might impact cotton quality traits can help breeders and researchers focus on developing new varieties tailored to these changes. These insights are crucial for the sustainable and profitable advancement of the cotton industry in the face of climate change. Despite the advantages of this study, there are certain limitations.

The study assumes that water and nutrients are not limiting factors and, therefore, the main factor influencing fiber quality is temperature. In reality, water and nitrogen stress can occur during the cropping period, which can impact the fiber quality. Although the influence of water and nitrogen stress is not considered, functional equations on the relationship between different nitrogen and water stress levels and their impact on fiber quality have already been published (Lokhande and Reddy, 2014b; Lokhande and Reddy, 2015). In this study, we did not consider these relationships mainly because accounting for them requires detailed information on the amount of irrigation, rainfall, fertilizer application, the timing of fertilizer application, and other management practices.

In this study, equal weightage was given to all four fiber quality indices during the planting date optimization, assuming equal importance to each quality index (fiber strength, length, micronaire, and uniformity). Depending on the significance of individual indices, optimization could be performed by adjusting the weightage assigned to each quality index.

The functions used in the study have not considered the impact of temperature on pollination or boll shedding at higher temperatures, which is crucial to consider. For instance, Oosterhuis and Snider (2011) found that the number of fruiting sites increased by 50 % as the temperature rose from 30°C to 40°C. In contrast, the number of squares and bolls dramatically decreased with an abscission percentage of 80 % (Oosterhuis and Snider, 2011). Furthermore, the young bolls are susceptible to shedding when grown at an average daily temperature of 32°C or higher (Oosterhuis and Snider, 2011; Reddy et al., 1996).

In the present study, the counties considered for analysis are those where cotton has been grown in the past 15 years. The same number of counties is used in future weather analysis. However, as temperatures rise, more counties (especially towards the north of the currently grown cotton region) could become suitable for cotton growth. This possibility was not considered in this study. Future research could also consider counties where cotton cultivation could become viable due to more favorable temperature conditions.

5. Conclusion

The study developed a methodology to estimate the optimum planting dates for maximizing fiber quality (fiber length, strength, micronaire, and uniformity). By considering factors such as temperature, GDD, and cotton variety, the methodology identifies suitable planting windows for each location and each cotton variety. Genetic algorithm is used to determine the best planting date within the planting window, ensuring optimum planting dates maximize fiber quality. The fitness function for the genetic algorithm is fiber quality, which combines four key fiber quality indices (fiber strength, fiber length, micronaire, and uniformity) by giving equal weightage. The proposed methodology is presented for the cotton belt in the USA; however, it can be adopted for any other location or spatial region. The maps of the optimum planting dates and fiber quality provide a general outlook on the potential variations in planting dates needed to improve fiber quality.

The study also offered insights into the possible variations in planting dates and fiber quality in relation to future weather conditions. The study showed that even when planting at the optimal dates, fiber quality can decrease with an increase in temperatures (future climate scenarios) for all the fiber quality indices (length, micronaire, uniformity) except for fiber strength. Micronaire will be the most adversely affected fiber quality in the future, followed by length and uniformity. Fiber strength will have an advantage in the future. The study also concluded that planting early-season varieties late can lead to higher fiber quality. Additionally, the study showed that cotton can be grown in more counties as temperatures increase in future weather scenarios for all cultivars.

In conclusion, this study addresses a crucial aspect of cotton production by developing a methodology to estimate optimal planting dates to maximize fiber quality. Cotton is a significant global commodity, and cotton quality plays a pivotal role in the cotton production sector, impacting both growers and industries. While previous research studies have often focused on increasing cotton yield, this study fills a critical gap by emphasizing the enhancement of cotton quality.

This methodology offers cotton growers and researchers a practical tool to optimize planting dates for improved fiber quality, potentially reducing financial losses for the cotton industry. By enhancing fiber quality through planting date optimization, this study supports cotton production's sustainability and economic viability.

CRediT authorship contribution statement

Sahila Beegum: Writing – original draft, Software, Methodology, Formal analysis, Conceptualization. **Kambham Raja Reddy:** Writing – review & editing, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Shrinidhi Ambinakudige:** Writing – review & editing. **Vangimalla Reddy:** Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

I have shared the link for the data

Acknowledgments

This study is based on work supported by Mississippi State University, Mississippi, the United States Department of Agriculture, Agricultural Research Service (under Agreement No. 58-8042-9-072), and the USDA NIFA 2019-34263 30552 and MIS 043050 and NSF QIA 2316382. The authors also received support from the University of Nebraska, Lincoln.

Code availability

Source codes developed in this study for estimating (a) the earliest planting time, (b) last planting time, (c) optimum planting dates using genetic algorithm optimization procedure, (d) estimation of the potential fiber quality can be accessed from https://github.com/sahilabeegum/OptimumPlantingDateFiberQuality.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2024.109483.

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