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MOLECULAR BIOLOGY AND PHYSIOLOGY

A Method to Estimate the Effects of Temperature on Cotton Micronaire

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ABSTRACT

Differences in micronaire of cotton fiber can affect grower returns, and influence textile quality. Therefore quantifying those effects that influence micronaire are important in developing management practices to optimise micronaire. This study proposes a method for predicting seasonal crop micronaire. The aim was to quantify the response of micronaire to temperature during boll filling and assess this information's ability to predict micronaire on an independent dataset. Utilising existing data from sowing time experiments in Australia that spanned three decades, linear responses of micronaire to both daily average and minimum temperatures were developed (r^2 =0.68 for both). These responses coupled with an estimate of temperature during the boll filling period when the majority of bolls were undergoing fiber thickening were able to successfully predict the micronaire on an independent dataset (r^2=0.42) despite no adjustment for other climate and management factors that may influence crop micronaire. The ability to predict temperature effects on micronaire will be useful to assess reasons for seasonal and regional differences in micronaire and assess opportunities to modify micronaire with changes in management practices that influence the timing of boll development.

Micronaire (no units) of cotton is a fiber quality trait that reflects a combination of fiber linear density (often referred to as fineness) and fiber maturity (Lord and Heap, 1988). Too high micronaire (> 4.5) may indicate that fiber is coarse and is undesirable for spinners as it results in too few fibers in yarn cross section, reducing its strength. Too low micronaire (< 3.8) may mean that fibers are immature, leading to breakages in fibers within the yarn and poor dye uptake during textile processing. As a consequence growers may incur price discounts if micronaire of their cotton falls outside the optimal range (3.8 to 4.5) (Bange et al., 2009; Bednarz et al., 2002; Gordon and Naylor, 2004).

The degree of fiber thickening or fiber maturity, contributes to differences in micronaire. When comparing fibres of similar perimeter the thicker the layers of cellulose laid down the more mature the fiber, and the higher the micronaire. Since fiber is primarily cellulose any influence on net crop photosynthesis and carbohydrate production will have similar influence on fiber thickening.

It therefore stands to reason that as photosynthesis is highly influenced by temperature (El-Sharkawy and Hesketh, 1964); sustained changes in temperature during the fiber thickening period will lead to differences in micronaire. In addition, studies of cotton fiber development using cultured cotton ovules have shown that cool temperatures during secondary wall thickening affected cellulose deposition leading to differences in fiber weight (Haigler et al., 1990; Roberts et al., 1992). These studies provided evidence to suggest that temperature influences on fiber development were also ovule specific during this phase, and was not entirely dependent on carbohydrate supply; reinforcing the significant effects of temperature on micronaire.

Many studies have shown that micronaire responds to temperature changes (Gipson and Joham, 1968; Hesketh and Low, 1968; Gipson and Ray, 1970; Wanjura and Baker, 1985; Liakatas et al., 1998; Reddy et al., 1999). Radiation (Pettigrew, 1995; Wang et al., 2006); plant defoliation (Siebert et al., 2006; Bange et al., 2010); water stress (Hearn, 1994); and competition among bolls for carbohydrate within the plant (Brook et al., 1992; Pettigrew, 1995), have also been shown to affect micronaire. A fundamental understanding

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of the degree of these influences on micronaire is important so that management practices can be developed to optimise micronaire.

Wanjura and Supak (1985) have used this understanding to predict or analyse consequences of temperature on micronaire. In this paper an alternative approach for predicting seasonal crop micronaire is proposed and tested. The response of micronaire to temperature was developed from micronaire measured from sowing time studies, and the use of a new approach to estimate the temperature during the fiber thickening phase of a crop's boll filling period was used. The ability of this approach to predict micronaire was tested against an independent dataset. This approach can be utilised to predict or analyse the effects on seasonal temperatures on micronaire such that management decisions may be refined to improve micronaire.

MATERIALS AND METHODS

Estimating temperature effects on micronaire. Fiber development for an individual boll occurs between flowering and boll maturity (defined as a cracked boll). This period is often referred to as the boll period. Fiber development during the boll period can be divided into three phases: fiber elongation, secondary wall thickening, and maturation (Ryser, 1999). For *Gossypium hirsutum,* fiber elongation occurs over approximately 20 d (Gipson and Joham, 1968; Gipson and Ray, 1969; Benedict et al., 1973; Meinert and Delmer, 1977), but this period can vary with temperature (Gipson and Joham, 1968, 1969; Gipson and Ray, 1969). Fiber thickening leading to differences in micronaire occurs over a period of approximately 40 d (Shubert et al., 1973; Benedict et al., 1973) following fiber elongation and similarly varies with temperature (Gipson and Joham, 1968).

To estimate the period of fiber elongation and fiber thickening leading to differences in micronaire, thermal time of an average boll period of 68 d (750 day degrees (DD)) (Constable, 1991; Hearn and Constable, 1984; Constable and Shaw, 1988) was divided proportionally using 20 d for fiber elongation and the following 40 d for fiber thickening. This equates to a 220 DD for the fiber elongation period and 440 DD for the fiber thickening phase. The remaining time is considered the fiber maturation phase in which the fibers dry, causing the vacuole (lumen) to collapse and the fiber to die.

Fiber quality data for these studies came from multisite experiments over a number of seasons. In order to determine any relationship between micronaire and temperature, it was necessary to retrospectively estimate development as above. Micronaire was compared with temperatures during mid boll fill, specifically from about 1200 to 1440 DD from sowing. These dates were chosen to represent the stage when the majority of bolls in a crop were estimated to be at the fiber thickening stage. Some earlier bolls would not have reached fiber thickening at 1200 DD and some later bolls may still be thickening after 1440 DD. Those points in development were chosen as follows:

The start of flowering was estimated as 777 DD (Constable, 1991) after sowing. Cold shocks delay flowering when minimum temperature reaches or falls below 11°C (Hearn and Constable, 1984). It was assumed that these crops required ten fruiting nodes to contribute to the majority of yield (Constable, 1991). The mid point of flowering was therefore five nodes after first flower (at 42 DD per node, or 210 DD). Since fiber elongation occurs in the first 220 DD after flowering, the point when all bolls have reached the fiber thickening stage is 777+210+220 = 1197 DD. Fiber thickening is complete for the first bolls when 777+660 = 1437 DD. From that point, successive bolls are mature, and the period when all bolls are thickening ceases. Daily average and minimum temperature are then calculated for this fiber thickening period.

Day degrees (DD) were derived using a base temperature of 12°C (Constable and Shaw, 1988):

$$\text{Day degrees} = \left[\left(T_{\max} - 12\right) + \left(T_{\min} - 12\right)\right] / 2 \qquad (1)$$

where T_{max} and T_{min} are daily maximum and minimum temperatures respectively. When $T_{min} <$ 12°C, $T_{min} = 12$. (or $(T_{min} - 12) \geq 0.0$).

Response of micronaire to temperature. To develop a relationship to temperature during the boll filling period of crop development measurements from sowing time experiments were utilised. These studies were grown with full nutrition and water requirements with sowing time, season, and location, all contributing to differences in temperature experienced by the crop during boll filling. Details of each experiment are presented in Table 1.

Table 1. Details of sowing time experiments used to generate the responses of micronaire to temperature. Origin of all cultivars are from CSIRO† Australia unless specified. Average cultivar micronaire values were measured by CSIRO's cotton breeding program long term dataset. With the exception of the study by Constable et al. where micronaire was measured using an areolometer, all other micronaire measurements were measured using a High Volume Instrument (HVI). The highest and lowest daily average minimum and maximum temperatures recorded for each experiment are also shown. These temperatures were estimated using the approach proposed in this paper.

Year Sown	Location	Sowing dates	Cultivars	First Flower Measured	Published	Average Min. Temperature (˚C)	Average Max. Temperature (˚C)	Average Cultivar Micronaire
1969 1971 1972	Narrabri	Sep. 30, Oct. 10, Oct. 20, Oct. 30, Nov. 10, Nov. 20, Nov. 30	DP Smoothleaf (Deltapine USA), Short Sympodial	No	Constable et al. (1976) (1)‡	13.4 13.4 17.5	32.6 30.1 32.8	3.95
2002	Narrabri	24 Sep., 15 Oct., 11 Nov.	Sicot 189 Sicot 289B	Yes	Bange et al. (2008) (2)	17.8	36.4	4.19 4.49
2002	Hillston	27 Sep., 24 Oct., 27 Nov.	Sicala S40i Siokra V-16i	No	Bange et al. (2004) (3)	15.0	34.9	4.16 3.97
2002	Breeza	25 Sep., 16 Oct., 18 Nov.	Siokra S101i Sicala V3i	Yes	Unpublished (4)	12.6	33.5	3.97 3.98
2003	Narrabri	13 Oct., 5 Nov., 28 Nov.	Sicot 189R Sicot 289BR	Yes	Bange et al. (2008) (5)	15.7	34.9	4.04 4.29
2003	Breeza	26 Sep., 14 Oct., 4 Nov.	Sicala 43 Sicala 43B	No	Unpublished (6)	17.8	32.9	4.26 4.30
2004	Narrabri	6 Oct., 22 Oct., 28 Nov.	Sicot 189R Sicot 289BR	Yes	Bange et al. (2008) (7)	17.9	34.1	4.04 4.29
2004	Breeza	28 Sep., 14 Oct., 27 Oct.	Sicala V3BR Sicala 60BR	Yes	Unpublished (8)	14.5	33.8	4.16 4.47
2007	Narrabri	16 Oct., 13 Nov.	Sicot 71BR Sicot 70BRF Sicot F1BRF	Yes	Unpublished (9)	12.9	30.4	4.50 4.13 4.37
2008	Narrabri	16 Oct., 14 Nov.	Sicot 71BR Sicot 70BRF Sicot F1BRF	Yes	Unpublished (10)	15.7	32.8	4.50 4.13 4.37

†CSIRO (Commonwealth Scientific and Industrial Research Organisation Australia).

‡Number in parenthesis specifies the dataset label used in the micronaire versus temperature responses in Fig. 1.

For each treatment of each experiment, daily average and minimum temperature during boll development were derived using the methodology described above. For the Narrabri location, climate data was obtained using records from the Australian Cotton Research Institute. For other locations, climate data was obtained from records from the nearest major town to the experiment site using the SILO patched point dataset (Jeffrey et al., 2001) that uses Australian Bureau of Meteorology official weather stations. Where experiments recorded the date on which first flower occurred, this information was used to initiate the time when temperature was estimated, otherwise timing of first flower was predicted, as described above.

Micronaire for each sowing treatment (averaged across cultivars) for each experiment was then regressed with the derived daily average and minimum temperature. Regression analysis was used to fit both linear and quadratic functions (Sigma Plot ver. 11, Systat Software, Inc., San Jose, California). Relative improvement of the quadratic response over the linear response was tested using F-tests based on residual means squares (RMS) accounting for differences in the function's degrees of freedom (Cousens, 1985).

Predicting micronaire from temperature. For validation purposes micronaire was compiled for a number of commercial cultivars grown in cultivar evaluation studies undertaken by Cotton Seed Distributors (CSD). The cultivars were grown across a range of sites in existing cotton regions in Australia from southern New South Wales (NSW) to central Queensland (Qld) in crops sown from 2000 to 2007.

Micronaire from four CSIRO cultivars was compiled; Sicot 71, Sicot 71B, Sicot 71BR, and Sicot 71 BRF. These were chosen because they were the most widely grown commercially across regions

and years. The average micronaire of these cultivars obtained from the CSIRO's cotton breeding program long-term dataset were: 4.25 for Sicot 71; 4.38 for Sicot 71B; 4.5 for Sicot 71BR; and 4.13 for Sicot 71BRF. Details of cultivar evaluation data used are presented in Table 2.

For each cultivar grown at each site and every year, temperature during boll development was calculated using the approach for temperature estimation described previously. Climate data was again obtained from the SILO patched point dataset (Jeffrey et al., 2001) for the nearest major weather station (< 50 km).

Table 2. Details of information used for micronaire prediction validation from Cotton Seed Distributors (CSD) (Wee Waa, NSW, Australia) cultivar evaluation sites. The range of years in which the cultivar evaluation was conducted and number of sites (in brackets) is shown under respective cultivars. For example 01-05(5) means that the cultivar was evaluated between 2001 and 2005 at five sites in the location specified.

Location	State	Latitude / Longitude	Cultivar			
			Sicot 71	Sicot 71B	Sicot 71BR	Sicot 71BRF
Emerald	Qld	148.2/ -23.5	01-05(5)	05-07(5)	03-07(8)	07(2)
Moura	Qld	150.0/ -24.6		05-06(2)	06(1)	
Theodore	Qld	150.1/ -25.0	02-03(2)	07(1)	04-07(6)	07(2)
Byee	Qld	151.8/ -26.2			04-05(2)	
Murgon	Qld	151.9/ -26.2		05(1)		
Macalister	Qld	151.1/ -27.0		07(1)	04-07(4)	07(2)
Dalby	Qld	151.3/ -27.2	00-04(5)	06-07(2)	04-07(3)	07(2)
Cecil Plains	Qld	151.2/ -27.5		06-07(2)		07(1)
Bongeen	Qld	151.4/ -27.6				07(1)
Brookstead	Qld	151.4/ -27.8	01-02(3)	05(1)	06-07(2)	07(1)
St George	Qld	148.6/ -28.0	00-06(7)	06-07(2)	03-07(8)	07(2)
Toobeah	Qld	149.9/ -28.4				07(1)
Dirranbandi	Qld	148.2/ -28.6	00-03(3)	05(1)	04-06(2)	
Goondiwindi	Qld	150.3/ -28.6	00-06(10)	07(1)		
Boggabilla	NSW	150.4/ -28.6		05-07(2)	04-07(5)	07(1)
Mungindi	NSW	149.0/ -29.0	01-07(5)	05-06(2)	03-06(6)	07(1)
Collarenebri	NSW	148.6/ -29.5		06(1)	05(1)	
Moree	NSW	149.8/ -29.5	00-06(12)	05(4)	03-07(13)	06-07(6)
Walgett	NSW	148.1/ -30.0	01-04(3)		04-06(4)	
Bourke	NSW	145.9/ -30.1	00-04(3)		03-05(4)	
Wee Waa	NSW	149.4/ -30.2	01-07(5)	05(1)	03-07(7)	07(2)
Narrabri	NSW	149.8/ -30.3	00-01(3)		03-06(3)	07(1)
Boggabri	NSW	150.0/ -30.7		05-07(2)	03-07(5)	07(1)
Gunnedah	NSW	150.3/ -31.0	01-04(4)			
Breeza	NSW	150.5/ -31.2	01-03(3)		02-07(7)	07(2)
Warren	NSW	147.8/ -31.7	01-05(4)		04-06(4)	
Trangie	NSW	148.0/ -32.0			04-06(4)	07(1)
Narromine	NSW	148.2/ -32.2	01-03(3)		03-05(2)	
Menindee	NSW	142.4/ -32.4	01-05(3)	05(1)	04-05(2)	
Hillston	NSW	145.5/ -33.5	01-07(7)		04-07(7)	07(2)
Hay	NSW	144.9/ -34.5			04-05(2)	

Sowing time of the CSD cultivar evaluation studies was the only variable needed to predict daily average and minimum temperatures. These temperatures were then used to estimate micronaire from the linear responses of micronaire to daily average and minimum temperatures.

To assess the performance of this approach to predict micronaire, predicted micronaire was plotted against the measured (observed) micronaire. Accuracy of predictions was quantified using the root mean square deviation (RMSD) between a number (n) of predicted (P) and observed (O) paired results:

$$RMSD = \left[\sum (O-P)^2 / n\right]^{0.5}$$ (Steele and Torrie, 1987)

RMSD represents a mean weighted difference between predicted and observed data. The linear regression of predicted versus observed values was used to quantify bias and the coefficient of determination (r^2) of this regression described the degree to which the data clustered around a straight line. Linear regression analyses were conducted using Sigma Plot (ver. 11, Systat Software, Inc., San Jose, California).

In an attempt to improve accuracy of prediction, inherent differences in micronaire (Mic_{adj}) of the cultivars were considered. Predicted micronaire was adjusted using the using the weighted average (micronaire 4.4) of the cultivars used to generate the micronaire versus temperature responses (Table 1), and the average micronaire of cultivars (Mic_{cuv}) used in the validation:

$$Mic_{adj} = Mic_{pred} - (4.4 - Mic_{cuv})$$

where Mic_{pred} is the predicted micronaire unadjusted for cultivar differences. The performance of this adjustment was assessed similar to micronaire predictions unadjusted for cultivar.

RESULTS AND DISCUSSION

Response of micronaire to temperature. Despite differences in cultivars that spanned three decades, micronaire was strongly related to average temperature that was estimated using the methodology detailed in this paper. Both the average of the daily minimum and average temperatures experienced during the period of fiber thickening contributing to final micronaire were similar in explaining changes in micronaire across all sowing times ($r^2 = 0.68$; Table 3; Fig. 1). The use of quadratic functions slightly improved r^2, but the improvement was not significant ($P < 0.05$) (Table 3). All experiments fitted the same regression.

Table 3. Results of regression analyses of micronaire versus daily average temperature and daily minimum temperature averaged for the estimated period of fiber thickening. Data used in this analysis is detailed in Table 1. Linear ($y = bx + c$) and quadratic regressions ($y = ax^2 + bx + c$) were tested for each variable. All regressions were highly significant ($P < 0.001$, $n = 46$). RMS – Residual Mean Squares for the fitted models.

Regression type and variable tested	r^2	*a*	*b*	*c*	RMS
Linear -Average daily temperature	0.68	-	0.19	-0.53	0.0722
Quadratic - Average daily temperature	0.69	0.81	-0.01	-7.99	0.0699
Linear - Minimum daily temperature	0.68	-	0.16	1.29	0.0726
Quadratic - Minimum daily temperature	0.70	0.48	-0.009	-1.40	0.0696

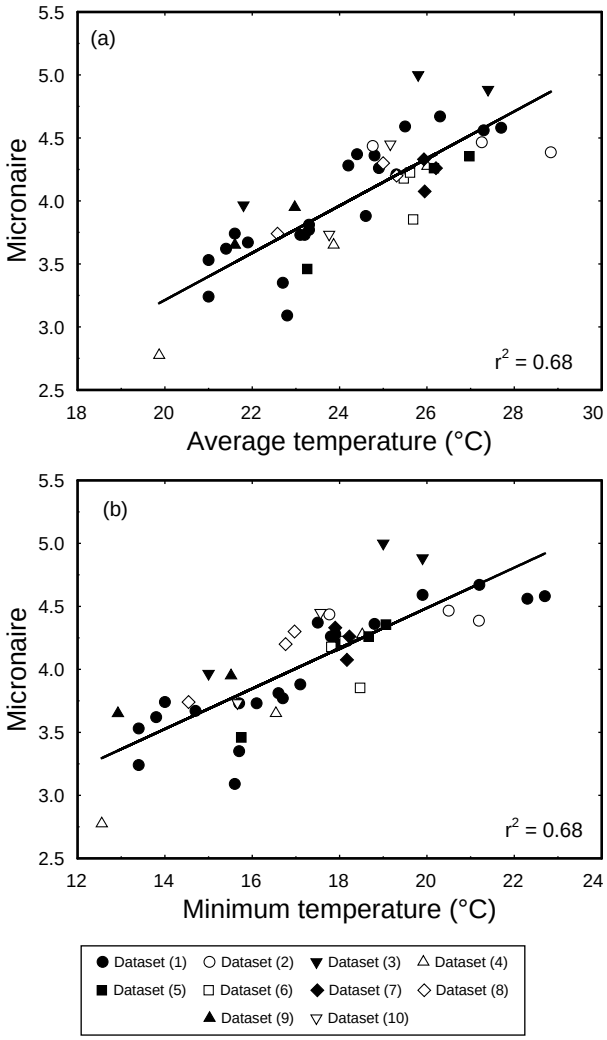

Fig. 1. The response of micronaire measured in sowing time studies to (a) daily average temperature and (b) daily minimum temperature during boll filling. Daily average and minimum temperatures were estimated using the approach proposed in this paper. Datasets are defined in Table 1.

Linear responses of micronaire to temperature have been previously reported (Gipson and Joham, 1968; Gipson and Ray, 1970) along with quadratic responses (Hesketh and Low, 1968; Wanjura and Baker, 1985). Reddy et al. (1999) had a linear increase in micronaire to daily average of 30.3°C and a linear decline after this temperature. In this study no significant decline in micronaire was measured when daily average temperature was 28.8°C and daily minimum was 22.7°C. While Wanjura and Baker (1985) used a quadratic response of micronaire to daily average temperature during boll development, their response showed no substantial decline in micronaire at 26.6°C. Hesketh and Low (1968) and Reddy et al. (1999) measured significant reductions in micronaire at daily average temperatures during boll filling of 33.5 and 32.3°C respectively. In studies on temperature effects on fiber development in cultured ovules Roberts et al. (1992) found no decline in cellulose synthesis with daily temperatures up to 34.0°C.

For micronaire measurements recorded at low temperatures, only studies of Gipson and Joham (1968) (minimum night 8.1°C) and Gipson and Ray (1970) (minimum night 11°C) had lower temperature treatments than those recorded in this study (daily minimum 12.6°C). It is most likely that with more data collected at higher and lower daily average temperatures, the response presented here (Fig. 1) would also be curvilinear.

The degree of change in micronaire with daily minimum temperature in this study (slope 0.16 micronaire units/^{o}C) was greater than measured by Gipson and Joham (1968) using night temperature. For average daily temperature the slope of the response (0.19) was less than that measured by Wanjura and Baker (1985) (slope 0.41 to 0.56) and similar to that of Reddy et al. (1999) (slope 0.21). Variations in these responses are expected as these studies differed in the way developing bolls were exposed to temperature regimes, and how final micronaire values were measured.

This study used daily average and minimum temperatures resulting from changes in sowing time in each experiment, which were applied to micronaire measurements resulting from all bolls harvested from the crop at the end of the season. Controlled environment studies that investigated temperature impacts on micronaire (Gipson and Joham, 1968; Hesketh and Low, 1968; Gipson and Ray, 1970) maintained minimum and maximum temperatures for longer periods throughout the day using square diurnal temperature control. Therefore impacts of higher and lower temperature extremes on micronaire may be greater resulting in temperature responses having lower slopes or being less responsive to temperature changes. In the Wanjura and Baker (1985) study, daily average temperature for individual cultivars were derived from 10 cohorts of bolls tagged over the duration of crop development. It would therefore be expected that a greater range of temperatures would be recorded during boll development and that the range and differences in micronaire would be larger resulting in more sensitive (greater slopes) micronaire versus temperature responses.

Predicting micronaire from temperature. Despite taking no account for other factors that influence micronaire (Constable and Bange, 2007), the methodology that estimated temperature proposed in this study coupled with the micronaire and temperature responses developed (Table 3) were able to predict micronaire well, both on a regionally and temporally diverse dataset (Table 4, Fig. 2) (r^2 0.33 to 0.42). Comparing the ability of daily average and minimum temperature responses to predict micronaire of the CSD data, they were similar in r^2, while the daily average temperature response had less bias across the micronaire predicted (slope closer to unity). The minimum temperature response did however, slightly increase RMSD by 0.08.

Table 4. The regression coefficient (slope), the coefficient of determination (r^2), intercept, and RMSD (root mean square deviation) for predicted versus observed data for micronaire using average daily and minimum temperature for the estimated period of fiber thickening using Cotton Seed Distributor's (CSD) dataset. Table includes analysis of predicted micronaire adjusted for individual cultivar differences. (n = 270).

Analysis	Slope	Intercept	r^2	RMSD
Unadjusted for cultivar				
Average temperature	0.74	1.27	0.34	0.42
Minimum temperature	0.61	1.90	0.33	0.34
Adjusted for cultivar				
Average temperature	0.90	0.79	0.41	0.53
Minimum temperature	0.77	1.32	0.42	0.46

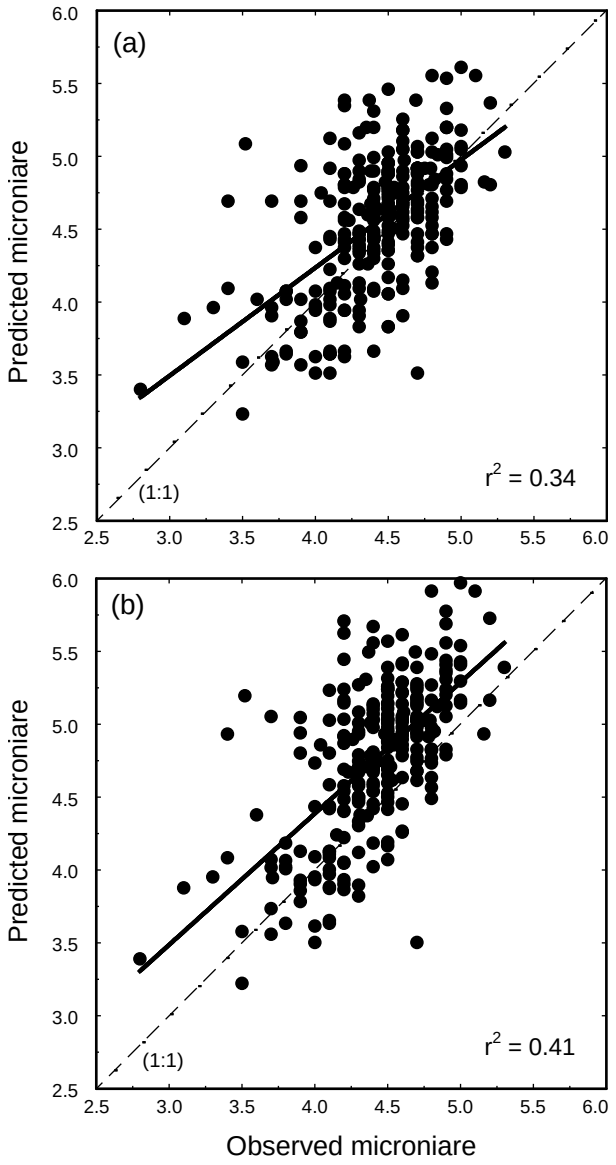

Fig. 2. Predicted micronaire versus observed micronaire for the fiber thickening period using Cotton Seed Distributor's (CSD) dataset: (a) micronaire estimated using the linear response of micronaire to daily average temperature (Table 3) un-adjusted for cultivar differences; (b) micronaire estimated using the same response adjusted for cultivar differences. Solid line is the line of best fit. Dashed line is the 1:1 line. (n = 270).

An adjustment in micronaire prediction to account for inherent cultivar differences reduced the bias and improved r^2 but RMSD was only slightly increased by 0.1 over the unadjusted prediction (Table 4, Fig. 2). This result was not unexpected given the limited range of inherent micronaire (Table 1) of the cultivars used for validation (range 0.12).

Considering the reasonable ability to predict micronaire, we see good opportunities to utilise this approach with confidence to explain or predict the effects of seasonal temperature on micronaire of crops. However, some issues would need consideration before applying this approach more broadly. In addition to extending the temperature range of the micronaire to temperature response mentioned previously, it would include the need for assessing cultivars that have considerably higher and lower inherent micronaire than those used in this study. The inherent micronaire difference of cultivars used was narrow (range 0.55) (Table 1). To improve predictions overall, ongoing research is extending the approach presented here to target the period of micronaire development to capture the combined effects of water stress, changes in boll load, and temperature.

Application of methodology. Utilising historical climate data, this approach has been used in the Australian cotton industry to assess reasons for seasonal and regional differences in micronaire and assess opportunities to improve micronaire with changes in sowing time (e.g. Fig. 3) (Kelly et al., 2006; 2008). These data demonstrate the importance of avoiding low micronaire as a result of late sowing and also indicates the frequency of high micronaire, which needs to be addressed by crop management and by breeding cultivars with lower linear density. This methodology will also be able to predict the whole of seasonal effects on micronaire at the time of harvest aid application and so assist in determining the risks and costs of earlier applications (Wanjura and Newton, 1981). The opportunity also exists to conduct research to predict the components of micronaire (linear density and maturity), which may assist in understanding the impact of climate on fiber quality and resulting textile performance.

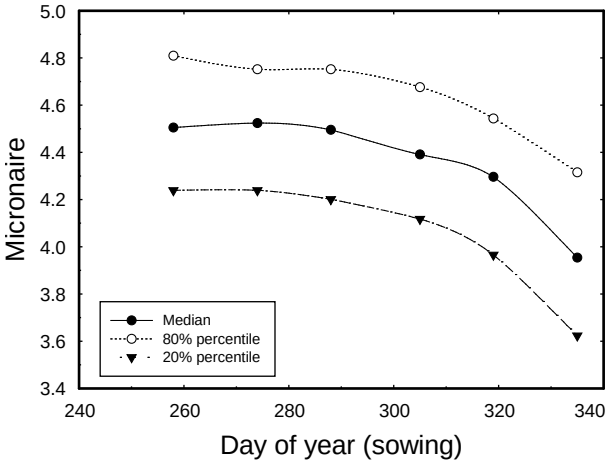

Fig. 3. An example of the use of micronaire predictive capability detailed in this paper to assess the impact on sowing time for Narrabri, NSW, Australia. The micronaire prediction uses the daily average temperature. The median and percentiles are calculated from micronaire predictions for 120 years of temperature data.

CONCLUSION

This study proposed methodology to predict the impacts of temperature on micronaire of cotton crops. This understanding coupled with knowledge of the degree of the effects of radiation, plant defoliation, and competition from bolls for carbohydrate within the plant will improve predictions as well as developing management practices to optimise micronaire.

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