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Negative associations still exist between yield and fibre quality in cotton breeding programs in Australia and USA

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ABSTRACT

This research demonstrates the negative association between cotton (*Gossypium hirsutum* L.) yield and fibre quality (length, strength, micronaire, fineness and maturity) through time and on two continents. In Australia (AUS), six years of experiments with intermediate stage breeding material, selected on the basis of high quality were compared with eleven years of the USDA Regional High Quality Test (US), a component of the National Cotton Variety test. Stepwise linear regression was used to measure the association of quality with yield. Overall, fibre length and strength had significant ($P < 0.001$) negative association with yield; fibre maturity had a positive association, while micronaire and fineness were inconsistent between years. The mean association for fibre strength in AUS data meant that a strength improvement from 314 to 333 kN m kg^{-1}, was associated with a yield reduction of 1000 kg lint/ha. Yields were greater in AUS than in US, so there were generally steeper slopes for US data describing the negative association between fibre length and strength with yield. This research confirms that a negative association still exists between fibre quality and yield and highlights breaking of linkage as one possible component of progress being made in decreasing this association. Suggested breeding strategies include selecting lines that are outliers with better fibre and yield and to use those lines in a recurrent selection program. It was concluded that large population sizes, robust testing and intermating of retained elite lines are required in early segregating generations to ensure the rare combinations of good fibre and yield can be increased and identified.

1. Introduction

In order to broaden the portfolio of upland cotton (*Gossypium hirsutum* L.) fibre types for delivery into Asian high-count ring spinning, cultivars with better combinations of fibre length, strength and fineness (linear density) are desirable. Such fibres will address an increasing demand for lightweight casual cotton garments; particularly in China and India (Liu et al., 2010). To address that aim, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) has been breeding cotton genotypes with premium fibre adapted to Australian (AUS) conditions.

There is considerable evidence in the literature for strong negative associations between many important fibre properties and lint yield (Al-Jibouri et al., 1958; Meredith and Bridge, 1971). Based on these breeding studies, the most significant association appears between yield and fibre strength, with the degree of the association being population dependent. Culp et al. (1979) has the only documented success of overcoming strength and yield within his population, although the values of yield and strength were relatively low by today's standards. Fibre length has also been shown to be negatively associated with yield within intraspecific *G. hirsutum* populations (Scholl and Miller, 1976; Tyagi, 1987; Zeng and Meredith, 2009) while interspecific crosses with *G. barbadense* tend to show a non significant association (Mei et al., 2004; Percy et al., 2006). Al-Jibouri et al. (1958) is citied for having found no significant association with length and yield in an upland cross, however the original parents did not differ in length.

Such negative associations inhibit the development of elite cultivars competitive in yield with existing cultivars of base fibre quality. This has created a dilemma in cultivar development, delivery and adoption. Clearly cotton producers require a price premium to compensate for yield penalties and so encourage production of premium fibre types. The historical premium paid for California (CA) Acala compared with AUS base is US 15c/kg (US 7c/lb) (Ashley Power, Auscott Pty Ltd, pers comm., Sept 2011). Such a premium would make up for a 9% yield penalty. Producers have to trade off lower yield with higher price and are wary of this risk.

In this study we present data sets from a number of sites and years from CSIRO breeding material aimed at premium quality. We measured the associations between lint yield and the fibre

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properties of length, strength, micronaire, linear density (fineness) and fibre maturity. We compare those associations with similar information from the United States Department of Agriculture (USDA) high quality cultivar data sets. Knowledge of the nature and extent of the association between yield and various fibre properties will assist with developing breeding strategies to minimise the yield penalty with combinations of premium fibre properties.

2. Methods

The CSIRO cotton breeding program in Australia has been developing populations targeting high fibre quality from crosses involving local germplasm but originating in part from US New Mexico (NM) Acala (Constable et al., 2001). In this program, populations are screened for fibre quality at the individual plant stage (usually F_3) and selections from those are advanced to progeny rows and screened again for quality and yield. The selected material then enters the replicated high quality experiments reported in this paper. Depending on performance, these breeding lines will either be discarded, be used as a parent and/or proceed for further evaluation.

Intermediate stage breeding material, at F_4, F_5 or F_6 generations, exhibiting high fibre quality were grown in field experiments at the Australian Cotton Research Institute (ACRI), Narrabri, NSW (30°S; 150°E) and either Moree, NSW (29°S; 149°E) or Mungindi, Qld (28°S; 149°E) from 2004 to 2009. The soil type is grey clay with heavy texture, classified locally as Ug 5.2 (Isbell, 1996). The US classification is a Typic Haplustert (USDA, 2010). Experiments were sown in late September or early October in rows 100 cm apart aiming at 10 plants per metre of row. Crops were managed with full irrigation, spraying for pests as required and weed control by pre-planting herbicides such as Trifluralin and Fluorometuron followed by inter-row cultivation prior to flowering. Each plot was three rows x 14 m long and the centre row was harvested by a plot picker at maturity. A 350 g subsample was taken for determining lint fraction on a 20 saw gin and for fibre quality measurements on a high-volume instrument (HVI) 900 (HVI 1000 in 2009) (USTER Technologies Inc., Charlotte, NC) and Shirley Fineness Maturity Tester-3 (FMT) (Shirley Developments Ltd., Stockport, England). The experiments were grown with four replications in a Latinized alpha design (Williams, 1986) with AUS and US controls (Table 1). Although one to two Pima genotypes were included in each experiment, their data are not reported in this paper. Restricted maximum likelihood (REML) analysis, in GenStat, (Payne et al., 2009) was applied for processing individual trials by taking account of spatial effect over field row and block.

This AUS data were compared with similar data from the High Quality Regional Cotton Variety tests in the US as provided by Ellen Keene for 1999 to 2009, combined across locations (USDA, 2011). These trials contained mainly elite cultivars and fixed lines and were grown at up to 11 sites across the US cotton belt with the objective of evaluating the performance and adaptation of genotypes. Fibre quality data were measured by HVI and arealometer. We calculated fineness in US data by converting the reported arealometer weight fineness to the same units as FMT (μg/m). The US data were from randomised complete block designs, and were analysed by ANOVA in SAS (SAS institute, 2008). The genotype × location interaction was used as the error term in F tests (USDA, 2011).

The AUS data had a total of 376 data points over six years while the US data had 224 data points over eleven years. Step-wise linear regression analysis, using GenStat, was performed separately on both AUS and US data for the association between lint yield (averaged across sites in each country) and fibre length, strength, micronaire, fibre maturity and fineness. The regression firstly fitted all data across years; secondly tested for a different intercept each year; and finally tested for different intercept and slope each year. Six out of the ten regressions had significant differences ($P < 0.05$) between years in intercept and slope; the other four regressions had the same slope for all years.

Table 1
Field locations, number of entries and controls for Australian experiments 2004–2009.

Year	Locations	Number of entries	AUS Controls	Controls originating from US
2004	ACRI	60 (9)[a]	Namcala[b] Sicot 71 Sicot 80 Sipreme	Acala Maxxa GTO Acala 1517-88 GC 510 Del Cerro 8810 Pima[c]
2005	ACRI, Moree	72(7)	Namcala Sicot 71 Sicot 81 Sipreme	Acala Maxxa GTO Acala 1517-88 8810 Pima
2006	ACRI, Moree	77(7)	Namcala Sicot 71 Sicot 81 Sipreme Sipima 280	Acala Maxxa GTO Acala 1517-88
2007	ACRI, Moree	54(9)	Namcala Sicot 71 Sicot 75 Sicot 81 Sicala 350B Sipima 280	Acala Maxxa GTO Acala 1517-88 8810 Pima
2008	ACRI, Moree	66(5)	Sicot 71 Sicot 75 Sipima 280 Sicala 350B	Acala Ultima
2009	ACRI, Mungindi	60(6)	Sicot 71 Sicot 75 Sipima 280 Sicala 350B Sicala 340BRF	Acala Ultima

[a] Number of total entries followed by number of controls in parenthesis.
[b] Namcala is Acala 1517-70, grown in Australia in the 1970's.
[c] 8810 Pima (Percy and Turcotte, 1998).

3. Results

All fibre quality measures had significant associations with lint yield in both data sets, being consistently negative for fibre length and strength, but more variable for micronaire, fineness and maturity (Table 2).

3.1. Fibre length

Fig. 1 shows the negative association between HVI fibre length and yield across years for US and AUS data. The relationship had significantly different intercepts ($P < 0.001$) with the same slope for each year in each country (Table 2). However it is clear the slope of the negative association was lower for the AUS data (−0.00028 ± 0.00017 mm/kg/ha) than US data (−0.00340 ± 0.00045 mm/kg/ha, Table 2) and there were a greater number of higher yielding genotypes with longer fibres in the AUS data. Outliers in the AUS data with yields less than 2000 kg/ha were generally the US controls – all US Acala types. Though having relatively long fibre, these CA and NM cultivars are not well suited to AUS soil type, climate, insect pest pressure and diseases. By omitting these cultivars in AUS data, the R^2 almost doubles to 0.21 ($P < 0.001$); intercepts increase by 3 mm to about 35.5 mm; and slopes increase (not shown). Outliers in the US data were two TAM genotypes, which had lengths greater than 32 mm with below average yield; the lower fibre lengths were MD and JACO genotypes from 1999.

3.2. Fibre strength

Fibre strength also had a strong negative correlation with yield across all years in the US and AUS data (Fig. 2). The AUS data had different slopes across years, with the greatest slope in 2008 (-0.0292 ± 0.00804 kN m kg^{-1}/kg/ha) and the least in 2004 (-0.0088 ± 0.00314 kN m kg^{-1}/kg/ha) (Table 2 and Fig. 2). The US data had the same slope across years (-0.089 ± 0.00882 kN m kg^{-1}/kg/ha), three times the steepest AUS slope in 2008. There were a few desirable outlier genotypes in the AUS data with strengths near 353 kN m kg^{-1} and yields above 3000 kg/ha. Again, when omitting the Acala cultivars, the intercepts and slopes increased for AUS data (not shown). The two strongest lint genotypes in US data were NM 03012 and NM 97051. Other outlier genotypes with high yield and strength were TAM 182-34 and FiberMax ‘FM 966’ with strengths of ∼353 kN m kg^{-1} (although FM 966 originates in AUS, it has strength of about 314 kN m kg^{-1} in AUS or US commercial practice). Acala ‘Maxxa’ and ‘Ultima’ had strong influence on the slope with its high strength and lower yield.

3.3. Micronaire

For micronaire, the AUS data had significantly positive slopes across years, while 2006 and 2009 had the lowest intercepts at 2.6 and 2.7 micronaire units respectively (Fig. 3 and Table 2). The lowest micronaire values were low yielding genotypes with Acala background. Micronaire values can shift across years based on specific populations as well as climate and management. The influential AUS years were 2004, which had a wide range of micronaire 3.5–4.5

Table 2
Slope and intercepts for yield regressed against fibre quality traits for US and AUS data sets based on stepwise regression analysis.

Trait	Location	Year	Intercept	s.e.	Slope	s.e.	R^2
Length (mm)	US	1999	31.3	0.50			
	US	2000	31.8	0.28			
	US	2001	32.8	0.28			
	US	2002	32.8	0.27			
	US	2003	33.1	0.29			
	US	2004	34.6	0.32	-0.00340	0.00045	0.45***[a]
	US	2005	33.8	0.29			
	US	2006	33.8	0.28			
	US	2007	33.5	0.27			
	US	2008	34.2	0.29			
	US	2009	33.7	0.28			
	AUS	2004	31.8	0.49			
	AUS	2005	32.4	0.18			
	AUS	2006	32.1	0.15	-0.00028	0.00017	0.11***
	AUS	2007	32.5	0.17			
	AUS	2008	32.3	0.15			
	AUS	2009	32.6	0.16			
Strength (kN m kg^{-1})	US	1999	396	9.90			
	US	2000	394	5.59			
	US	2001	414	5.39			
	US	2002	423	5.29			
	US	2003	422	5.68			
	US	2004	429	6.27	-0.08908	0.00882	0.35***
	US	2005	406	5.68			
	US	2006	415	5.59			
	US	2007	407	5.39			
	US	2008	428	5.68			
	US	2009	401	5.49			
	AUS	2004	354	9.02	-0.0088	0.00314	0.32*
	AUS	2005	392	14.8	-0.0257	0.00608	
	AUS	2006	380	15.3	-0.0182	0.00539	
	AUS	2007	355	16.2	-0.0136	0.00608	
	AUS	2008	403	22.4	-0.0292	0.00804	
	AUS	2009	375	25.4	-0.0189	0.00892	
Micronaire	US	1999	4.8	0.40	-0.00024	0.00039	0.27**
	US	2000	5.6	0.65	-0.00109	0.00063	
	US	2001	5.0	0.53	-0.00049	0.00050	
	US	2002	4.7	0.53	-0.00014	0.00048	
	US	2003	4.5	0.67	-0.00006	0.00058	
	US	2004	4.9	0.74	-0.00035	0.00059	
	US	2005	3.5	0.77	0.00068	0.00067	
	US	2006	4.3	0.66	0.00030	0.00058	
	US	2007	2.4	0.65	0.00155	0.00058	
	US	2008	3.9	0.58	0.00052	0.00051	
	US	2009	4.1	0.52	0.00047	0.00050	
	AUS	2004	3.8	0.19	0.00011	0.00007	0.40*
	AUS	2005	3.6	0.31	0.00028	0.00013	
	AUS	2006	2.6	0.32	0.00048	0.00011	
	AUS	2007	3.3	0.34	0.00013	0.00013	
	AUS	2008	3.5	0.47	0.00017	0.00017	
	AUS	2009	2.7	0.54	0.00048	0.00019	

Table 2 (*Continued*)

Maturity (%)	US	1999	84.5	1.52			
	US	2000	85.2	0.84			
	US	2001	83.8	0.82			
	US	2002	86.9	0.81			
	US	2003	85.0	0.86			
	US	2004	74.0	0.96	0.00284	0.00137	0.61***
	US	2005	78.9	0.86			
	US	2006	84.3	0.84			
	US	2007	81.9	0.82			
	US	2008	84.3	0.88			
	US	2009	81.5	0.83			
Maturity Ratio	AUS	2004	0.9	0.03	0.000010	0.00001	0.37*
	AUS	2005	0.8	0.04	0.000026	0.00002	
	AUS	2006	0.7	0.04	0.000060	0.00002	
	AUS	2007	0.8	0.05	0.000016	0.00002	
	AUS	2008	0.9	0.06	-0.000008	0.00002	
	AUS	2009	0.8	0.07	0.000024	0.00003	
Fineness (μg/m)	US	1999	116.9	17.60	-0.00560	0.01700	0.22**
	US	2000	159.2	28.30	-0.05120	0.02760	
	US	2001	132.2	23.30	-0.02070	0.02180	
	US	2002	126.8	23.00	-0.01550	0.02110	
	US	2003	42.6	29.20	0.04690	0.02540	
	US	2004	156.0	32.10	-0.02490	0.02580	
	US	2005	66.1	33.70	0.03400	0.02900	
	US	2006	98.0	28.80	0.01110	0.02540	
	US	2007	53.8	28.30	0.04580	0.02540	
	US	2008	71.5	28.50	0.02870	0.02440	
	US	2009	94.6	22.80	0.01420	0.02170	
	AUS	2004	149.1	7.43	0.00371	0.00260	0.31*
	AUS	2005	151.5	12.20	0.00963	0.00496	
	AUS	2006	120.7	12.50	0.01599	0.00440	
	AUS	2007	150.2	13.30	0.00386	0.00498	
	AUS	2008	136.5	18.40	0.01080	0.00657	
	AUS	2009	98.7	20.80	0.02248	0.00734	

* Indicate significance at 0.05.
** Indicate significance at 0.01.
*** Indicate significance at 0.001.

and high lint yields; 2005, which was lower yielding - seen in the cluster at approximately 2300 kg/ha and about 4.5 micronaire; and 2007 with lower micronaire values and a range of yield. However the most influential data were the Acala cultivars; by omitting them from the dataset the slopes became equal with a positive average slope of 0.00371 ± 0.00006 micronaire units/kg/ha (not shown). In the US data, the slope changed from significantly negative to significantly positive after 2005. The lowest micronaire values were NM genotypes 03N116B, 03S1023 in 2007 and N1155 in 2005. Arkot 9610, Stoneville 'ST4892BR', Phytogen 'PHY485WRF' and 'CS 44' had micronaire values above 5.0 in 2006; while Acala Maxxa had the three influential low micronaire points at ~500 kg/ha.

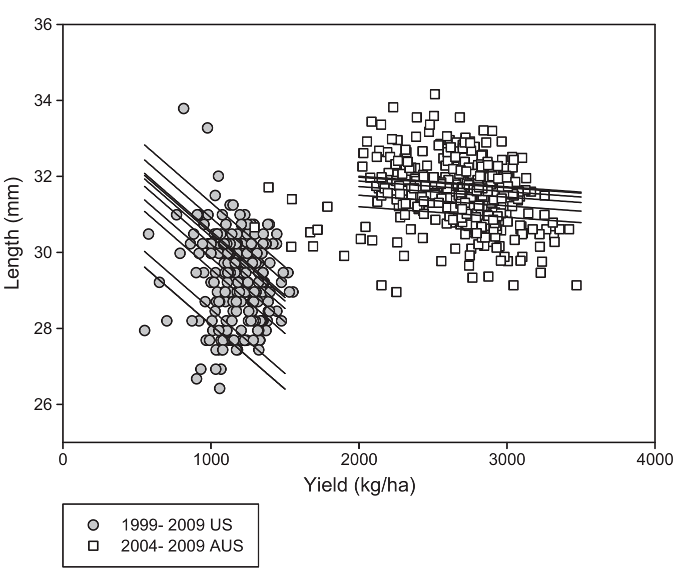

Fig. 1. Regression of yield on fibre length for various years in AUS and US. Regression and correlation coefficients presented in Table 2.

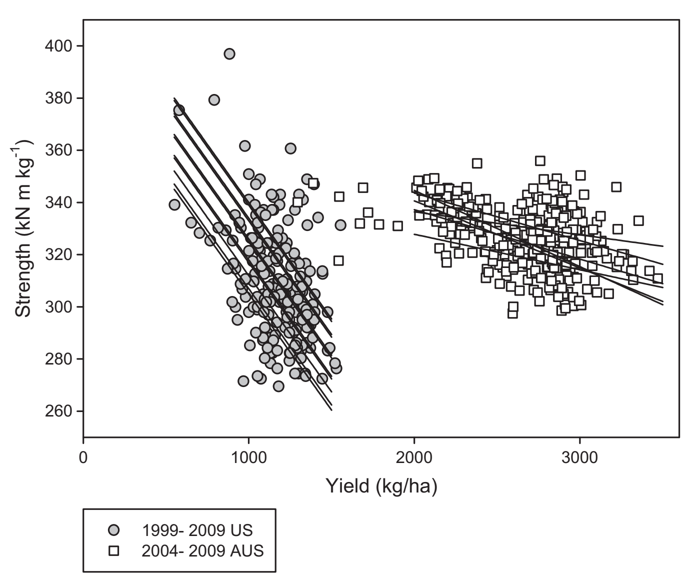

Fig. 2. Regression of yield on fibre strength for various years in AUS and US. Regression and correlation coefficients presented in Table 2.

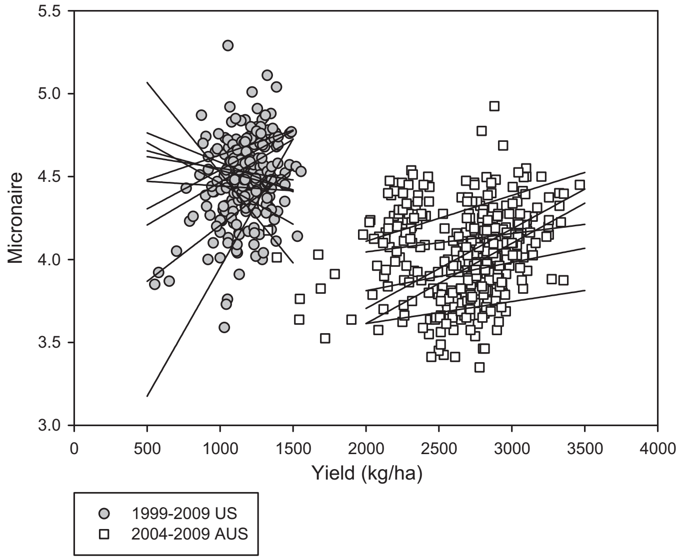

Fig. 3. Regression of yield on fibre micronaire for various years in AUS and US. Regression and correlation coefficients presented in Table 2.

3.4. Fibre maturity

AUS data had a wider range of yield and maturity ratio compared with the US maturity percentage data (Fig. 4). The intercept and slopes for AUS data were different, with 2008 being not significantly different from zero (Table 2). The regression explains 0.61 variation in the US data, while only 0.37 in the AUS data. Outliers in AUS data include the 2004 growing season which had a number of genotypes with high maturity ratio and high yields. There were also a number of genotypes with low maturity ratio in 2006 and 2007. The range of maturity percentage in US data were 73–96% but varied with year. For instance, 2004 had a range of 73–81% while 2002 was 88–96%. Outliers consisted of five FM cultivars, Phytogen Seed Company 'PSC355' and NM 030212 for high maturity percentage; while the 2004 growing season accounted for eleven low maturity percentage outliers.

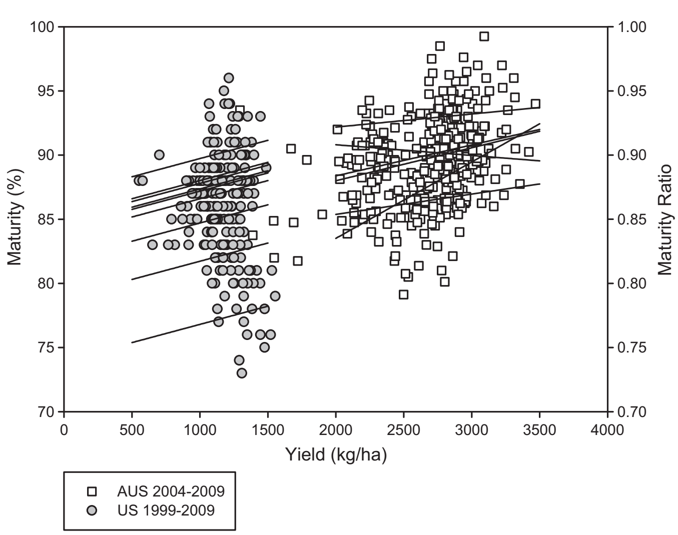

Fig. 4. Regression of yield on fibre maturity for various years in AUS (maturity ratio) and US (maturity percent). Regression and correlation coefficients presented in Table 2.

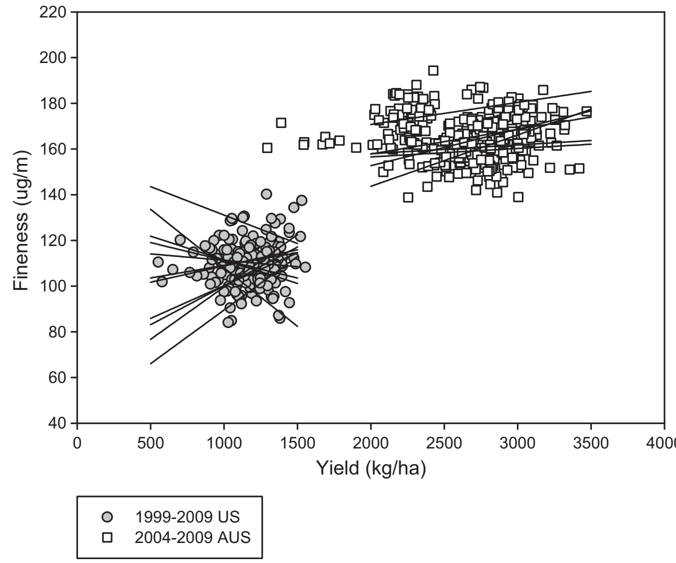

Fig. 5. Regression of yield on fibre fineness for various years in AUS and US. Regression and correlation coefficients presented in Table 2.

3.5. Fineness/linear density

Values from each country differ because of different instruments used; FMT in AUS and arealometer in US. Associations between fineness and yield gave similar results to micronaire and yield; the countries had significantly different slopes and intercepts (Fig. 5 and Table 2). The AUS data had a wide range in yield with Acala cultivars yielding less than 2000 kg/ha. As with micronaire, when the Acala cultivars were omitted the slope became the same across years. In the US, with the exception of 2003, years prior to 2005 had significantly negative slopes and after 2005, shifted to significantly positive. 'ST4892BR' and Arkot 9308 had the highest fineness values of 140 and 137 μg/m respectively, in 2004. Acala Maxxa and Acala Ultima were influential points due to their lower lint yields in the US data.

4. Discussion

The US experiments contained more fixed lines but entries also changed each year, as new candidates became available. The US data represented the average of up to 11 sites each year but any genotype × environment interaction in that data were ignored for the sake of comparing mean yield and fibre quality with AUS data.

We have highlighted that Acala cultivars have been general outliers with lower than average yield for their length and particularly strength values in US and AUS data sets (Figs. 1 and 2). Acala cotton has been developed in western US with particular attention to fibre properties and Verticillium Wilt (*Verticillium dahliae*) resistance and for some period under a one cultivar law in CA (Smith et al., 1999). As a result they tend to be lower yielding in regions outside of their origin (Zhang et al., 2005). Thus Acala cultivars may have been penalised by using overall mean yield across sites in US data. This was particularly the case from 1999 to 2004 with few sites in western US. In 2005–2009, the research added Las Cruces, NM, improving the relative performance of Acala types (USDA, 2011).

Many of the previous studies on fibre quality and yield associations occurred from the late 1950's to the late 1970's (Al-Jibouri et al., 1958; Miller and Rawlings, 1967; Meredith and Bridge, 1971, 1973; Culp and Harrell, 1973; Culp et al., 1979). Though those studies made advances in fibre quality and suggested breeding strategies to overcome linkage associations, current premium cultivars require higher yield combined with longer and stronger fibre. Our targets for premium fibre are length 32 mm and strength 333 kN m kg^{-1} with yield within 5% of the Australian control cultivar, 'Sicot 71'.

Recently Campbell et al. (2011) in describing breeding progress with Pee Dee germplasm in the US shows increasing yield (28 kg/ha per breeding group). However length and strength were reduced, so the negative association between yield and length and strength was retained. The slopes we have calculated from Campbell et al. (2011) data were −0.0045 mm/kg/ha for length and −0.076 kN m kg^{-1}/kg/ha for strength, similar to the US data we calculate here (Table 2 and Figs. 1 and 2).

4.1. Fibre length

Fibre length had a lesser negative association with yield than did strength (Table 1). That result is consistent with length being more affected by climate and management than is strength (Constable and Bange, 2007). Fibre length can be strongly affected directly by water status - irrigation (Hearn, 1994; Palomo-Gil et al., 2004) and by nutrient deficiency to a lesser extent (Hearn, 1981).

However the association between yield and length is still strong. If anything, length can be a positive yield component if all other yield components are held constant (Coyle and Smith, 1997), so there should not be a negative association unless longer fibres' require more energy to sustain more turgor. For AUS breeding material, we believe we now have a number of lines with length at our target of 31.8 mm and good yield (Fig. 1) and that result may be an indirect way of concluding the negative association is linkage (Meredith and Bridge, 1971; Smith and Coyle, 1997). In addition, the observation that the negative association between yield and fibre length is dependent on the genetic population (Constable and Bange, 2007) would support the linkage theory.

4.2. Fibre strength

May (2002) speculated that increased fibre strength may require higher energy demands and so higher strength genotypes yield less than lower strength lines. Pettigrew (2001,2008) found strength was increased by higher light and temperature; however the difference was not sufficient for it to cause a yield penalty. Timpa and Ramey (1994) reported a direct correlation between the molecular weight of cellulose and fibre strength. Although cotton fibres are about 95% cellulose at maturity, there are other polysaccharides such as aribinose, galactose and xylose (Meinert and Delmer, 1977) and pectins (Micheli, 2001; Wang et al., 2010) which may be important in determining fibre strength by joining cellulose fibrils. Although these polysaccharides have a higher metabolic cost (Amthor, 2010), it seems unlikely that a higher metabolic cost for such small fractions of the fibre would be a yield drain unless transport of complex polysaccharides was an issue. More research should be done on these fundamental reasons for negative association between yield and fibre strength.

A simple strategy of developing better combinations of yield and quality is recurrent selection; identifying outliers in the association with improved yield and quality and utilising those outliers in further crossing to make gradual improvements over generations. Miller and Rawlings (1967) were able to increase yield by 30% by using three cycles of recurrent selection; selecting the highest yielders, intercrossing, advancing to replicate trials and repeating. Their data show a negative strength and yield association in the base population and a non significant association after the fourth cycle of recurrent selection. This technically proves that the linkage was broken even though the strength values were not particularly strong; reiterating the need for selection targets. It also supports that recurrent selection will work if the reason for the negative association was linkage (see also Meredith and Bridge, 1971; Meredith, 1984).

4.3. Micronaire, fineness, fibre maturity

Associations with yield across countries and years were more consistent with fibre maturity than with fineness or micronaire (Figs. 3–5), although different instruments were used to measure fibre maturity and fineness in each country.

Micronaire tends to be influenced more by environment than genetic differences (May, 1999) and it is notable in the significantly different slopes and intercepts between years for both locations (Fig. 3). The AUS dataset is consistent with Bange et al. (2010), in that micronaire was lowest in the coolest growing season, 2007 (data not shown). In the US data, the slope changed from significantly negative to significantly positive after 2005 (also noted by Kerby et al., 2007).

The literature shows that yarns spun from lower micronaire fibre (implied as lower linear density) can have improved yarn strength (Virgin and Wakeham, 1956; Iyengar and Gupta, 1974; Subramanian et al., 1978). Similarly Kloth (1998) and Hequet and Wyatt (2001) showed low perimeter fibre was important to improve yarn strength. These positive effects of lower micronaire, linear density or perimeter on improving yarn strength are due to higher number of fibres in a yarn cross section. It has therefore been suggested that micronaire is not the best measurement for estimating fineness because it confounds maturity and fineness, and it is an inferior measure for predicting yarn quality (Raskopf, 1966; Abbott et al., 2010; Long et al., 2010). Lord (1956) presented an early review of the issues in resolving fineness and maturity components of micronaire and this dilemma led to subsequent development of other instruments such as arealometer, FMT, AFIS and Cottonscan (Abbott et al., 2010) to directly measure fibre fineness or maturity.

4.4. Breeding strategies

This paper has highlighted benchmark associations between yield and fibre quality. Target slopes for the association between fibre quality and yield in breeding populations are: length: <−0.00028 mm/kg/ha; and strength: <−0.0020 kN m kg^{-1}/kg/ha. Such a slope for fibre strength for example represents a yield reduction of 1000 kg lint/ha for an increase of 19.6 kN m kg^{-1} strength and the magnitude of that loss highlights the challenge in identifying lines with desired combination of yield and strength. Further, individual genotypes exceeding the fitted trend by more than one standard deviation need to be targeted for future use in crossing or evaluation. Breeding lines with high yield and desirable fibre provide appropriate parents for recombination in further crossing.

In the AUS data, the frequency of lines with greater than average yield and exceeding the regression trend by more than one standard deviation were 7.9% for length, 9.3% for strength and 1.1% for length and strength. These statistics further emphasise the negative associations with yield and provide a strong indication that larger breeding population sizes may be required to identify desired combinations of fibre properties with yield. The Australian breeding populations started with about 700 individual plant selections and reduced on average to about 10 elite lines per cross (i.e 1.4%) with two generations of evaluation and selection before entry into these experiments. Increased population sizes therefore would require substantially increased resources at the early stages of breeding. Culp et al. (1979) showed similar numbers in starting with thousands of selections and only having desirable strength in a ratio of 1:300. Once intermating was done between superior plants, the frequency of desirable combinations increased. Therefore, recurrent selection should be used as part of the breeding strategy to more effectively assemble desired alleles for yield and fibre quality as well as to weaken and/or break their negative relationship.

5. Conclusion

Fibre length and strength (negative) and maturity percentage (positive) showed consistent and highly significant associations with lint yield across these two data sets. Micronaire and fineness did not have consistent associations with yield. We therefore conclude that there were definite negative associations between high yield and desirable quality levels in cotton breeding populations in Australia and US. The literature is not clear on reasons for these associations and precise study of those reasons is required to develop strategies for breaking the associations. Larger population sizes, eliminating families with high negative association between yield and quality and recurrent selection with the best combination of yield and quality are suggested as strategies to utilise at present. Breeding for genuine length and strength improvements at modern yield levels have not had 100 years of effort. The CSIRO program in Australia has only had about 12 years of specific effort. We cannot claim success yet but the identification of targeted strategies is a positive step forward for breeding.

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