Validation of novel in-field monitoring techniques to assist harvest aid timing in cotton

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Abstract
Australian cotton systems rely heavily on chemical harvest aids allowing for mechanical harvest. Poor timing of application of these chemicals can reduce both fibre yield and quality, and lead to increased costs at harvest. Too early applications increase the amount of immature fibre, reducing yield and affecting spinning and dye uptake during textile processing. Too late applications subject crops to weathering from rainfall, reducing both harvest efficiency and optimal fibre colour. Novel methods assisting decision making at the time of harvest aid application have previously been developed. These include determining the risk of fibre entanglement (neps) formation at harvest, an estimation of the potential final crop fibre micronaire at harvest, and the development of a mathematical relationship between the proportion of immature bolls with traditional measures of overall crop maturity. Neps and micronaire are related to both fibre and crop maturity. Utilising independent datasets, this study further validated these novel methods for Australian cotton systems and highlighted their utility for assisting with harvest aid timing decision. This paper also makes recommendations on how these approaches may be used in conjunction with sensing technologies to further assist in maintaining crop yield and quality.

Keywords: *Gossypium hirsutum*, temperature, fibre quality, decision support, micronaire, neps

Introduction
In cotton production systems the micronaire value represents a combination of fibre maturity, linear density, and diameter. Maturity relates to the degree of thickening of the cell wall during fibre development. Too high micronaire may indicate that fibre is coarse and is undesirable for spinners as it results in too few fibres in yarn cross section, reducing its strength. Too low micronaire may mean that fibres are immature, leading to breakages in fibres within the yarn and poor dye uptake during textile processing. Additionally, immature fibres with little cell wall thickening (and which give a low micronaire value) will be more prone to nep (small fibre entanglements) formation during mechanical manipulation such as lint cleaning. Neps are undesirable as they decrease mill processing efficiency and typically absorb less dye and reflect light differently and may appear as ‘flecks’ on finished fabrics.

Ensuring optimum micronaire and minimising neps are critical quality management issues for the Australian cotton industry. Growers in Australia are discounted when micronaire is too high or too low (optimum range is 3.8 to 4.9). While there is currently no discount to growers when there is a high incidence of neps, it can affect overall industry reputation when cotton arrives at the spinning mill (Bange *et al.*, 2018). Management practices that force open immature bolls to include in the harvest to increase yield or to reduce micronaire may increase the incidence of the textile issues described above . The accepted recommended practice for harvest aid application is to apply harvest aids when around 60% or more of the bolls on a crop are open (Bange *et al.*, 2018).

Assisting the decision when to time harvest aid applications (e.g. chemical defoliants), Bange *et al.* (2010) and Bange and Long (2011) developed novel methods for Australian cotton systems that: 1. Related the proportion of immature bolls at the time of harvest aid application with the potential level of neps increase, and thus provided a general recommendation of the level of immature bolls to avoid neps issues; 2. Predicted fibre micronaire at harvest from the micronaire of immature bolls at the time of harvest aid application; and 3. Established relationships of the proportion of immature boll number to total bolls around harvest aid application with traditional methods used to estimate crop maturity. Predicting all these elements can assist in determining if the timing of harvest aid application is optimal. While these methods were developed from several seasons, they had not been validated on independent datasets. This study presents the results of independent validations of these methods and makes recommendations on how these approaches could be used in conjunction with sensing technologies to assist with cotton harvest aid timing decisions.

Methods

Cultural details and measurements

Experiments (Exp.) that systematically imposed different timings of harvest aids were conducted at the Australian Cotton Research Institute (ACRI), Narrabri from 2008 until 2011 (three summer seasons; Exps. 1 to 3). All Exps. were planted in October using the Bollgard II® Roundup Ready® (Monsanto) *Gossypium hirsutum* cultivar Sicot 71BR (CSIRO, Australia). Crops were established and grown with full irrigation using non-limiting nitrogen and thorough insect control. Treatment plots (10 m by 4 m), contained four rows spaced at 1 m. In the centre two rows of each plot, harvest aids (leaf defoliant combined with a boll opener) were applied at approximately five to ten-day intervals starting soon after the first recorded open boll. This resulted in each Exp. having five harvest aid timing treatments, which included a control. The control was only treated at the recommended time for harvest aid application (greater than 60% open bolls). In all Exps. additional treatments were generated where the harvest aid timing treatments were also applied to plots that had fruiting branches removed at flowering to create more variable canopies. In Exp. 1 the first five fruiting branches were removed, while in Exps. 2 and 3 fruiting branches three and seven were removed.

To establish crop status when harvest aid treatments were applied a fixed area of 1m of the row in each control plot was monitored to determine the percentage of bolls open (defined as when two sutures on the boll had split). On each occasion, five plants were also taken from the control plots and the proportion of immature bolls and nodes above last cracked boll (NACB) were measured. Immature bolls were distinguished from mature bolls by cutting bolls perpendicular to their vertical axis and assessing the colour of the seed coats within the bolls. A seed coat that was not dark classified the boll as immature (Brecke *et al.*, 2001). In all Exps. lint samples from these immature bolls were collected. To determine final lint quality 10 m of each plot was harvested with a spindle picker and seed cotton ginned. Sub-samples of ginned lint were subjected to high volume instrument (HVI) testing (ACRI, Narrabri). In Exps. 1 and 2 further sub-sampling of fibre occurred and these were tested for total neps using the Uster AFIS PRO (CSIRO, Geelong). All Exps. were randomised complete block designs with treatments replicated four times. Harvest aids were sprayed with a calibrated CO_2 pressurised 3.0 m hand boom using a flat fan nozzles 100 L/ha of spray solution. The chemical and rates were: 0.2 L/ha Dropp Liquid® (active constituent Thidiazuron); 3 L/ha Prep 720® (active constituent Ethephon); and 2 L/ha D-C Tron® (active constituent Petroleum Oil).

Validation assessments

Here the existing published functions are presented and the approaches taken to validate them with data collected in these studies are both outlined. The first validation was the function that related the proportion of immature bolls (Imm_{bolls}) (% of the total bolls on the crop) within a crop at the time of harvest aid application with the potential nep level increase at harvest time. The intent of this function was to assess if harvest aids at the time of assessment would increase neps at harvest time (Bange *et al.* 2010):

$$Change\ in\ Neps = 3.90\ \times e^{0.048\ \times Imm_{bolls}} \qquad \text{Equation 1.}$$

Where 'Change in Neps' is the amount of total neps (count/g) beyond background neps at harvest time if harvest aids were applied at the time with Imm_{bolls}. Based on the current response the recommended level of immature bolls where neps risk is increased is beyond 30%. To assess if the current recommendation holds, data collected from Exps. 1 and 2 were used to generate a new response and compared with Equation 1.

The second validation was the function that predicts fibre micronaire at harvest from micronaire of collected immature bolls at the time of harvest aid application (Bange and Long, 2011). This function intends to establish if micronaire at harvest would be acceptable. Modifications of the timing of harvest aid application may improve chances of achieving micronaire within the optimal range:

$$Harvest\ Micronaire = (0.786\ \times MIC_{Imm}) + (0.009\ \times Open_{bolls}) + 0.948 \qquad \text{Equation 2.}$$

Where harvest micronaire is the micronaire estimate at harvest time, MIC_{Imm} is the micronaire of the immature bolls, and $Open_{bolls}$ is the proportion of open bolls at the time of harvest aid application. Micronaire of the immature fibre was shown to be a better indicator of the growing conditions of the crop before and at the time of assessment than fibre micronaire of open bolls (Bange and Long, 2011).

The third validation assessed two functions that related the proportion of immature boll number to total bolls and NACB around harvest aid application with traditional methods used to estimate crop maturity ($Open_{bolls}$) (Bange et al. 2010). The intent of these functions will assist in applying the above function (Equations 1 and 2) when alternative methods to estimate crop maturity are employed:

$$Imm_{bolls} = -0.82 \times Open_{bolls} + 78.16 \qquad \text{Equation 3.}$$

$$Imm_{bolls} = 10.07 \times NACB - 13.90 \qquad \text{Equation 4.}$$

For equations 2 to 4 performance in prediction was assessed by plotting the predicted values against the measured observations collected in this study (all relevant data collected from Exps. 1 to 3). The linear regression of predicted versus observed results was used to quantify bias with the slope of the regression.around Lin's concordance correlation coefficient (LCCC) was also calculated to assess the agreement of between the predicted and observed data. Higher the LCCC value the better the predictions, and values >0.90 can be considered moderate to excellent. The degree of accuracy of the predictions were also quantified using the mean absolute error (MAE).

Results and Discussion

Across experiments, the harvest aid timing treatments were able to vary the level of immature bolls by 18 to 76% in Exp. 1, 15 to 77% in Exp. 2, and 14 to 64% in Exp. 3. This resulted in significant micronaire variations amonst treatments and between years (4.38 to 4.48 in Exp. 1, 3.21 to 3.97 in Exp. 2, and 4.32 to 4.57 in Exp. 3). A change in neps from background neps in Exps. 1 and 2 ranged from a reduction in total neps of 45 counts/g to an increase of 227.

In validating the methodology to predict nep risk level from the Imm_{bolls}, the new response closely mimicked the response previously generated by Bange *et al*. (2010) (Figure 1). While data was variable, there was little evidence that neps were increased beyond background levels when harvest aid treatments were applied when less than 30% Imm_{bolls} are present. This confirms that the current industry recommendation of 30% (Bange *et al*. 2018) is suitable for avoiding issues with neps.

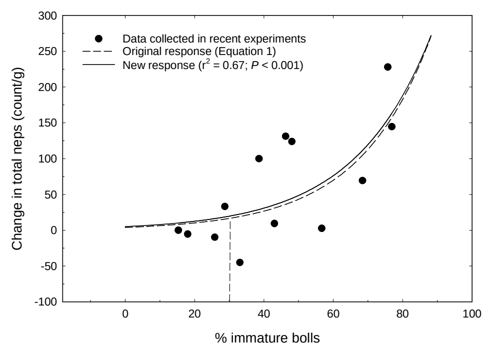

Figure 1. The change in total nep number at harvest in relation to the proportion of immature bolls at the time of harvest aid application. The graph shows the original response by Bange et al. (2010) and the new response generated from data collected in Exps. 1 and 2. The vertical dashed line shows the current recommended immature boll % above which neps risk level is increased.

Assessment of Equation 2 where final fibre micronaire at harvest was predicted from the micronaire of the collected immature bolls was reasonable (Figure 2) (LCCC = 0.70). Only four of the 18 estimates had predicted micronaire greater than 0.5 from the observed values with a MAE of 0.26. Of the four values that were not predicted well there was no consistent reason for their deviation. One possible reason is that the small sample sizes resulting from lint only collected from five plants made it difficult to obtain accurate readings from the HVI on all occasions. Research is currently investigating the use of portable handheld Near-infrared spectroscopy (NIR) to identify the degree of maturity of fibre contained within bolls to support this approach; avoiding the need to process samples using HVI.

Assessments of the relationships of Imm_{bolls} to both $Open_{bolls}$ and NACB (Equations 3 and 4) were also reasonable (Figure 3). Of these two relationships, the one that related Imm_{bolls} to $\text{Open}_{\text{bolls}}$ was a stronger relationship; as it had a similar slope, improved LCCC, and lower MAE compared to the relationship of

Imm$_{bolls}$ to NACB. Similar performance was also found by Bange et al. (2010). It is known that the NACB assessment is less useful in non-uniform canopies like those in this study with fruiting branches removed. The results also highlight the utility of using *Imm*$_{bolls}$ generated from sampling only five plants is effective in determining crop maturity (including non-uniform canopies).

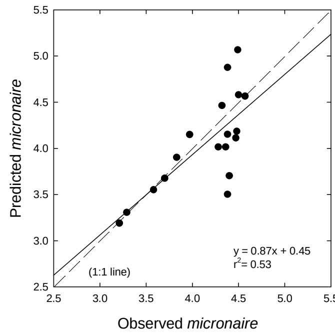

Figure 2: Predicted micronaire at harvest using Equation 2 versus observed micronaire measurements taken in this study. Solid line is the line of best fit. Dotted line is the 1:1 line.

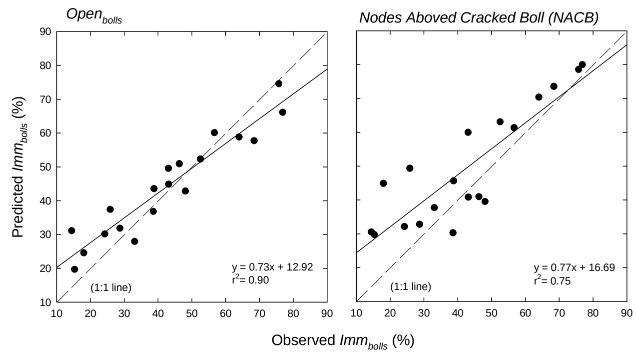

Figure 3: Predicted % of immature boll (I*mm*$_{boll}$) using Equations 3 and 4 versus observed measurements taken in this study. Solid line is the line of best fit. Dotted line is the 1:1 line. MAE and LCCC was 5.70 and 0.91 for the *Open*$_{bolls}$ relationship respectively; while it was 9.40 and 0.81 respectively for the NACB relationship.

Conclusions

With the additional independent validation undertaken in this study, these results have further demonstrated the utility of these methods to assist harvest aid timing decisions to improve fibre quality. If estimates of micronaire are low, the risk of increasing neps is possible. If climatic conditions are favourable, harvest aid timing could be delayed to allow further boll development and increase micronaire into the acceptable range. Conversely, if micronaire is high and neps risk low, harvest aid applications may occur earlier and avoid fibre damage from weathering. All these approaches presented here can be easily linked to current research efforts focussed on harvest time that are attempting count open bolls using either proximal or remote sensing approaches, as well as attempting to identify and quantify the maturity of bolls using technologies like NIR.

Acknowledgements

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