Australian Government
Cotton Research and Development Corporation

# FINAL REPORT 2014

## For Public Release

### *Part 1 - Summary Details*

*Please use your TAB key to complete Parts 1 & 2.*

**CRDC Project Number:** **UQ1302**

**Project Title:** Developing soil testing and fertiliser response guidelines to manage P, K and S fertility for irrigated and dryland cotton cropping systems

**Project Commencement Date:** 1 July 2012 **Project Completion Date:** 30 June 2015

**CRDC Program:** 1 Farmers

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**Date Submitted:** __________________

# *Part 3 – Final Report*

(The points below are to be used as a guideline when completing your final report.)

## *Background*

### 1. Outline the background to the project.

Current nutrient management strategies are based primarily on the concept of cost effective nutrient management (ie. deriving an economic return from fertilizer investment), unless managers have consciously embarked on either nutrient replacement or nutrient build-up approaches. The consequence of cost effective strategies is that soil fertility reserves of (currently) non-limiting nutrients will continue to decline until they, too, become limiting. The most common limiting nutrient in the clay soils of the northern cropping region is nitrogen (N), although phosphorus (P), potassium (K), zinc (Zn), and in some cases sulphur (S), appear to a lesser extent. Native reserves of P, K and S have been gradually declining such that there are an increasing number of situations where applications of varying combinations of these nutrients to both grains and cotton crops can result in significant yield increases. Collectively, these results suggest soil fertility constraints are increasingly likely to limit the Nitrogen and Water Use Efficiency in cotton crops and represent a challenge to profitability and sustainability in the long term.

One of the difficulties in dealing with these ‘new’ fertility constraints in soils that have traditionally had adequate indigenous nutrient reserves is identifying when the ‘fertility decline’ has reached the point where a change to the fertilizer program is warranted. Soil testing is one of the major tools growers and advisors use to monitor soil fertility and predict fertilizer requirements, but the ‘critical soil test value’ (the nutrient concentration below which a fertilizer response is considered highly likely) used to base these fertilizer decisions on are often relatively specific for the combination of soil type (e.g. alkaline cracking clays) and crop (e.g. cotton) being considered. With little prior evidence of widespread P, K and S requirements, the volume of research to develop robust and defensible critical values for the NE Australian cotton industry has not been undertaken and a clear need to develop these guidelines is now recognized. Part of this also recognizes the need to test deeper soil layers for status of immobile elements like P and K, as subsoil depletion is now widespread.

In addition to the lack of clear guidelines to identify responsive field sites, there are also issues surrounding the most effective fertilizer application strategies (rates, placement and timing) to allow the crop the best chance to recover and efficiently use the applied nutrient to produce yield. These issues are particularly important with immobile nutrients which don’t redistribute down the soil profile as soil moisture profiles refill. Where these nutrients are put is largely where they remain, and the ability of the crop to acquire nutrients from those fertilized zones has a large impact on the ability of the crop to respond to the applied nutrient. The most appropriate application strategy (banding or incorporation, band frequency/positioning) for each nutrient in different soil types and management systems (dryland v irrigated) is an area requiring considerable research attention.

This project has conducted an extensive field trial program to address these limitations with a clear focus on P and K responses, as both these nutrients figure prominently in cotton fertilizer programs. The field program has been supported by glasshouse studies on placement strategies for K, and by a field study exploring benefits from different organic matter amendments in cotton farming systems. There has been an attempt to integrate research findings with similar advances in N fertility management from other programs to collectively review existing, and develop improved, decision support tools to drive adoption of best practice nutrient management.

## *Objectives*

### 2. List the project objectives and the extent to which these have been achieved.

*2.1 Define critical soil test values (including appropriate soil sampling strategies and diagnostic methods) to indicate fertilizer P, K and S requirements for irrigated and dryland cotton cropping systems.*

The project approached this objective by focussing primarily on field trials to explore P and K responses on sites with contrasting soil test characteristics for P and/or K and where growers were actively using those nutrients in their fertilizer program. Research conducted in the previous phase of this project and in subsequent GRDC research has shown that the criteria to effectively select S-responsive sites was quite unreliable, and so there was very limited activity involving S in the project.

While critical soil test P and K values could be determined from the long term trial sites (in the case of K, on an atypical soil type for the cotton industry), the general lack of consistent responses to applied fertilizer in the 12 site years of field experimentation (6 P experiments, 5 K experiments and 1 experiment exploring the residual and interacting benefits of P, K and S applications) did not allow derivation of critical soil test values for either nutrient, and so this objective was not achieved. This failure was at least partly due to an inability to clearly identify responsive sites (despite industry guidance), combined with a repeatedly observed inability of the cotton crop to efficiently recover applied nutrient from fertilizer applied into, or at the base of, crop hills – especially under flood irrigation.

*2.2 Develop a suite of guidelines for fertilizer application strategies (rates, banding v mixing and fertilizer forms) to optimize cotton productivity in irrigated and dryland systems.*

The project has clearly demonstrated the ineffectiveness of banded P and K fertilizer applications, and unlike cereals, has also demonstrated the ineffectiveness of altered in-band constituents (e.g. adding P or N and P to K bands) as a way of improving exploitation of banded nutrients. Cotton was demonstrably more effective at exploiting P and K from applications which were dispersed through a large soil volume (eg. mixed in with tillage) than through bands. However, clear negative impacts of flood irrigation on root activity in those soil layers where nutrients were most readily dispersed (ie. the hill/bed) limited the effectiveness of this application strategy in irrigated crops.

The project also was able to clearly demonstrate the relative ineffectiveness of foliar applications of P and K as a strategy to overcome poor P and K acquisition from fertilized soil layers in irrigated systems.

*2.3 Develop a framework to allow nutrient budgets to be developed for irrigated and dryland cotton and grains-cotton farming systems. This will integrate outcomes from projects focussed on P, K and S with those on N in both farming systems.*

An extensive database of seed P and K concentrations has been developed from the field trials conducted during the project, but consistent with the lack of yield responses to applied fertilizer it is impossible to use this data to identify critical seed P or K concentrations associated with low yielding crops. Nutrient removal rates were determined primarily by seed removal for P (4-6 kg P/t seed) and by both seed (8-10 kg K/t seed) and lint (4-5 kg K/t lint) removal for K. The variability in concentrations between sites and treatments was relatively small, but these have been influenced by the general lack of strong yield responses in most trials.

*2.4 Lead a nationally coordinated extension & development program for crop nutrition and nutrient management issues.*

There is a far greater knowledge and understanding by growers and consultants on the use, management and behaviour of the key macronutrients phosphorus, potassium and sulphur in cotton cropping soils following the D and E activities undertaken by the key researchers and extension officers. This has included the nutrition module in myBMP being reviewed and updated with respect to new research outcomes and Nutripak being reviewed and in a position to be revised and updated.

## 3. Detail the methodology and justify the methodology used. Include any discoveries in methods that may benefit other related research.

The research component of the project has been strongly focussed on field research, using both small plots and commercial strips, with some supplementary glasshouse work to improve understanding of key processes.

Field experiments were established at sites on commercial farms under flood irrigation on the Darling Downs (Nangwee, Jandowae and Chinchilla) and north of Goondiwindi, while dryland sites were established at Warra, north of Moree and Tulloonah (although the latter ended up being sown to sorghum as the planting window was missed). The irrigated sites explored the interactions between nutrient application rate and application method (banding vs mixed into the soil with tillage), interactions between P and K at sites where both were expected to be limiting and the role of supplementary foliar applications to overcome poor recovery from soil. The dryland sites were restricted to banded applications and P*K interactions.

These intensive P and K trials were complimented by establishment of cotton in long term P (Colonsay, a rainfed site on the inner Darling Downs) and K (Taabinga, an irrigated site near Kingaroy) trial sites, which provided an opportunity to benchmark the nutrient status of trials on the commercial sites against sites with well dispersed nutrient in the cultivated layer and a wide range in crop nutrient status. These contrasts have proved to be pivotal in interpreting the generally limited field responses to applied nutrient in the sites established on farms.

Another long term trial site exploring the efficacy of organic amendments (manures and composts) that had been established in the preceding project was also maintained near Cecil Plains, with the effectiveness of annual applications of amendments on rainfed cotton and winter cereal production assesses annually and cumulatively across a 5 year treatment cycle.

A number (6) of broadly distributed, less intensive sites were also established to quantify the effectiveness of top dressing P and K in irrigated systems – a practice found to show visual responses in the preceding wet 2010/11 and 11/12 crop seasons. There were 3 site years on the Darling Downs and 2 west of Moree. A further site was established to look at K application strategies at Bongeen. These trials were established in the 12/13 and 13/14 seasons, with the lack of any significant responses resulting in the postponement of further studies until site selection and effective application strategies could be devised.

The nutrition research program was conducted in collaboration with the Nutrition Working Group and contributed to a nationally coordinated nutrition extension program lead by Mr Duncan Weir. This work has complemented similar activities conducted for GRDC in the grains industry that will collectively help to develop more profitable and sustainable nutrient management practices for the grains and cotton industries. While the derivation of soil test – yield response calibrations for P and K in cotton was not successfully achieved, there were clear findings around the most effective application strategies. The strong links to existing extension activities and professional networks have ensured development and dissemination of best practice principles to industry via improved decision support systems (eg. myBMP).

***Results***

**4. Detail and discuss the results for each objective including the statistical analysis of results.**

*4.1. Defining soil test-crop response relationships for P and K*

The characteristics of the on-farm sites where P and K response trials were conducted are shown in Table 1 for irrigated (0-30cm) and dryland (0-10cm, 10-30cm) sites. The long term experiments are also shown for comparison, with site averages shown for all nutrients except those of interest (i.e. P and K).

**Table 1**. Ranges in selected soil chemical characteristics for on farm experimental sites where P and/or K experiments were conducted during UQ1302.

| Site | $pH_w$ | Colwell P | BSES P | Exchangeable K | Exchangeable Na | ECEC |
|---|---|---|---|---|---|---|
| **On farm, Irrigated** | | | | | | |
| 0-30cm | 7.5-8.5 | 10-24 | 28-120 | 0.3-0.6 | 0.8-3.7 | 25-49 |
| **Long term K trial, irrigated** | | | | | | |
| 0-10cm | 5.9 | 27 | 22 | 0.08-0.48 | 0.05 | 10 |
| 10-30cm | 6.5 | 20 | 18 | 0.04-0.19 | 0.10 | 9.8 |
| 0-30cm | 6.2 | 22 | 19 | 0.05-0.24 | 0.07 | 9.8 |
| **On farm, Dryland** | | | | | | |
| 0-10cm | 6.9-8.3 | 6-30 | 47-60 | 0.4-1.1 | 0.4-1.1 | 22-41 |
| 10-30cm | 8.5-8.8 | 3-7 | 8-13 | 0.2-0.5 | 0.2-2.9 | 27-45 |
| **Long term P trial, dryland** | | | | | | |
| 0-10cm | 8.7 | 8-75 | 41-205 | 1.6 | 2.3 | 65 |
| 10-30cm | 9.1 | 5-15 | 28-54 | 1.0 | 4.9 | 72 |

Results from the long term field sites at Colonsay (P – Fig. 1, conducted in collaboration with Incitec Pivot and UNE1501) and Kingaroy (K – Fig. 2) have very clearly demonstrated that strong growth and yield responses to enrichment of depleted soil profiles can be achieved in the case of both P and K, and that it is possible to derived relationships between fertilizer responsiveness and a pre-plant soil test in the appropriate soil layers.

Our intention had been that we would be able to use the crop response data from the field experimental program on grower sites to test these soil test-crop response relationships (on the basis of relative yield – $Y_0/Y_{max}$), but this was prevented by the lack of crop P or K acquisition and the few significant crop response obtained at any site.

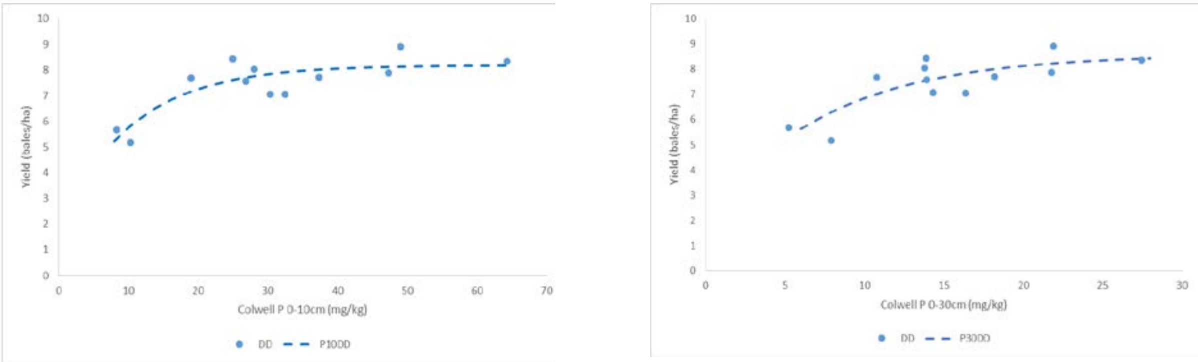



**Figure 1**. Relationship between pre-planting soil test for soil P status (Colwell P, mg/kg) and crop yield (bales/ha) for soil tests determined on (a) the 0-10cm soil depth, and (b) the 0-30cm soil depth. In dryland cropping systems such as at Colonsay a soil sampling regime of 0-10cm and 10-30cm is preferable, but most irrigated cotton producers test the 0-30cm test.

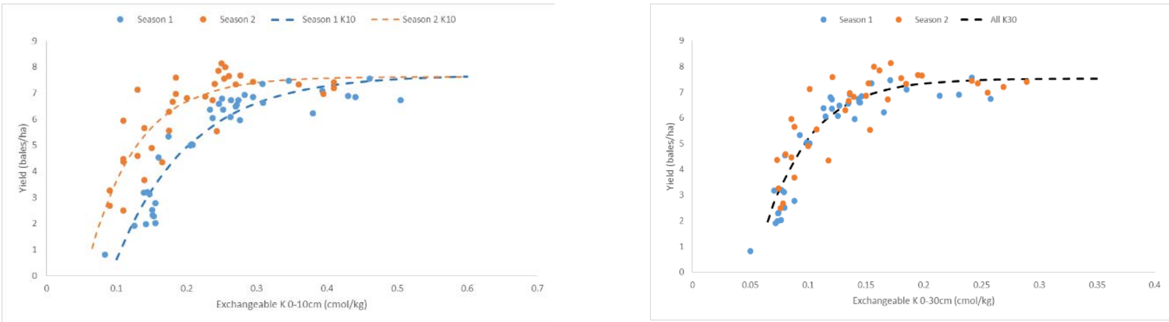



**Figure 2**. Relationship between pre-planting soil test for soil K status (exchangeable K, cmol/kg) and crop yield (bales/ha) for soil tests determined on (a) the 0-10cm soil depth, and (b) the 0-30cm soil depth. This site had supplementary overhead irrigation, so the appropriate sampling depth is uncertain, although the ability of the 0-30cm test to cater for seasonal variation was obvious.

There was really only one exception to this lack of significant yield response to the addition of a single limiting nutrient, and this was a response to applied K obtained in a dryland (and extremely water stressed) crop north of Moree in 2013/14 season (Figure 3). While potential yields were low (<3 bales/ha), the response to applied K increased yields by 45-50%, and increased linearly up to the highest rate applied (100 kg K/ha). This site had exchangeable K of 0.37 and 0.19 cmol/kg in the 0-10 and 10-30cm layers, respectively. That exchangeable K would have placed this site in the unresponsive part of the soil test-crop response curve developed at Kingaroy, which highlights the problem of extrapolation between soil types that differ markedly in soil properties that effect the soil K supply processes (eg. clay type, cation exchange capacity). While the P trial at Colonsay was on a Vertosol typical of the soils supporting most of the cotton industry (and so results should be broadly applicable), the K trial site was on a much lighter Brown Ferrosol with quite different cation exchange capacity and rates of diffusive supply for K. Collectively this limits the extent to which the K soil test-crop response can be used to guide K application on these heavier clay soils.

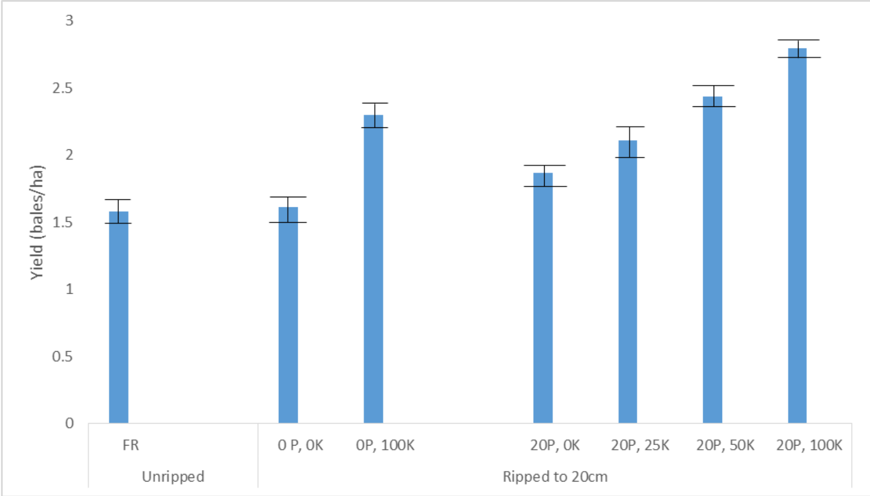



**Figure 3**. Responses to applied K fertilizer, with and without added P near Biniguy in a dryland cotton crop in 2013/14 season. Fertilizer was applied in bands 50cm apart and at ~20cm depth after harvest of the preceding crop in the rotation. Bars indicate standard errors of treatment means.

However, while the soil test-crop response relationships derived from this project are not necessarily translatable across the cotton industry, some of the internal use efficiency data collected from these sites can be used to benchmark crop performance, indicate the adequacy of P and K supply to the crop and also assess the effectiveness of the fertilizer program. The benchmark data derived from these core sites are outlined in Figure 4 below for each nutrient, with the slopes of the regression relationships indicative of the maximum internal K or P use efficiency (kg lint produced/kg nutrient accumulated in the crop).

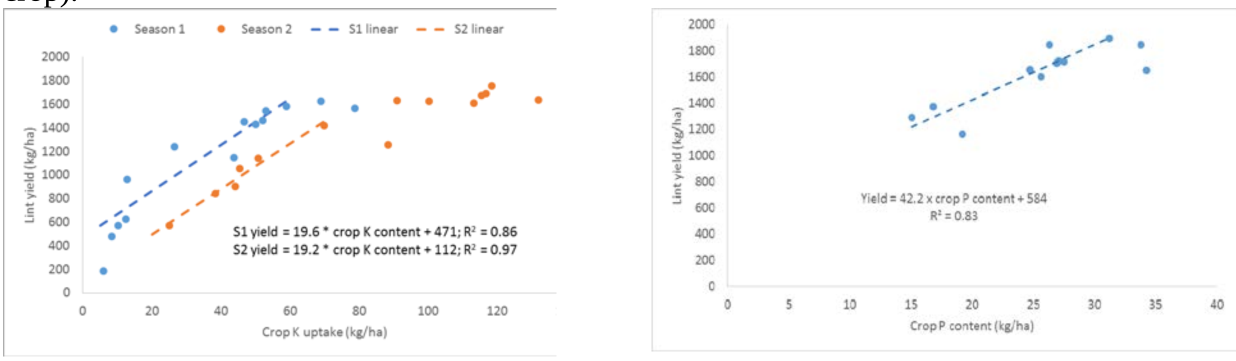



**Figure 4**. Relationship between yield (bales/ha) and (a) crop K uptake at Kingaroy and (b) crop P uptake at Colonsay (in collaboration with UNE1501). The dashed lines represent the internal nutrient use efficiency (kg lint yield/kg P or K uptake by the crop) when the respective crops were responding linearly to increasing crop access to the nutrient in deficit.

For consistency with published literature, these internal use efficiencies can be converted into units of kg P/K uptake required to produce 100kg lint yield, and are 5.1-5.2 kg K uptake/100 kg lint produced and 2.4 kg P uptake/100 kg lint produced, respectively. Data from the various field experiments where crop nutrient content and lint yield were determined in this project can then be compared to these benchmarks to indicate whether the crops grown at those sites would be expected to respond to applied P or K, and how effective these applications were at improving uptake or productivity. In the following table we report these benchmark PUE and KUE figures for the experiments undertaken in this project and its predecessor (UQ 00058, managed by GRDC).
Data from this analysis provides a number of key observations –

(i) Very few of the unfertilized experimental sites returned indices that suggested availability of K was limiting productivity. The exceptions were a dryland site on the Darling Downs (where indices were very low but no crop responses or significant K uptake was achieved) and another east of Moree (where a significant crop response was recorded and K uptake increased by 11-12 kg/ha in response to the highest rate of applied K fertilizer). The latter site (depicted in Fig. 3) achieved a yield response consistent with the internal KUE derived from Fig 4 (i.e. a lint yield increase of ~200 kg/ha in response to an additional 11-12 kg crop K uptake/ha).

(ii) Conversely, the P indices for the unfertilized crops were all lower than the 2.4 kg P uptake/100 kg lint produced (some as low as 20-25% of that value), and despite this suggesting crops should have been strongly P responsive, the lack significant yield increases was consistent with the limited impact of treatments on crop P uptake (typically < 2 kg P/ha derived from fertilizer).

(iii) With the exception of the single K responsive site (where the K index increased by ~30% in response to fertilizer application), there was minimal shift in either the P or K indices in response to applied nutrient, which was consistent with the generally poor uptake of applied P or K in crop biomass.

**Table 2.** Crop P and K uptake indices (crop nutrient content/100 kg lint produced) for the field experiments conducted in UQ00058 (with GRDC) and UQ1302 where nutrient uptake was determined. Shading indicates dryland crop sites.

| Locality | Year | **P trials** (kg P uptake/100kg lint) | | | **K trials** (Kg K uptake/100 kg lint) | | |
|---|---|---|---|---|---|---|---|
| | | Max yields (bales/ha) | PUE (no P fertilizer) | PUE (fertilized) | Max yields (bales/ha) | KUE (no K fertilizer) | KUE (fertilized) |
| Terry-hie-hie | 2010-11 | 2.0 | 1.8 | 1.8 | | 15.5 | 16.2 |
| Tulloona | 2010-11 | 2.8 | 1.5 | 1.7 | | 13.4 | 13.9 |
| Hopeland | 2010-11 | 5.6 | 1.5 | 1.7 | | 10.1 | 10.9 |
| Collarenabri | 2011-12 | 13.7 | 0.6 | 0.7 | | 5.7 | 6.0 |
| Terry-hie-hie | 2011-12 | 5.2 | - | 1.3 | | 8.9 | 8.1 |
| Warra | 2011-12 | 12.6 | 1.0 | 1.0 | | 6.9 | 6.7 |
| Warra | 2011-12 | 12.4 | - | 1.2 | | 7.7 | 7.6 |
| Warra | 2011-12 | 12.2 | 1.2 | 1.3 | | - | 8.8 |
| Warra | 2012-13 | 12.1 | 1.0 | 1.0 | | 6.7 | 6.9 |
| Terry-hie-hie | 2013-14 | 2.4 | 0.7 | 0.7 | | 3.7 | 4.7 |
| Jimbour West | 2013-14 | 5.1 | 0.4 | 0.5 | | 3.9 | 3.8 |
| Umbercollie | 2013-14 | 14.2 | 1.1 | 1.1 | | 10.0 | 9.2 |
| Hopeland | 2014-15 | 11.5 | 1.2 | 1.3 | | 6.6 | 7.2 |
| Nangwee | 2014-15 | 14.5 | 0.8 | 0.7 | | 6.5 | - |

At least some of the reason for the lack of consistent fertilizer P or K response may have related to the interacting effects of P and K, which are partly illustrated in the dryland trial in Fig. 3 and reinforced from the much higher yielding irrigated trial in Fig. 5 below. In the dryland example the lint yield response to P application alone was small and not statistically significant (16% increase, or ~60 kg lint/ha), but addition of K alone produced a larger response (42% increase, or ~150 kg lint/ha) and the combined effect of P and K together produced the largest response (73% increase, or ~270 kg lint/ha). In P trials at that site where background applications of K were made to ensure K deficiency did not limit the P response, no significant effects of added P were observed.
A similar effect can be observed in the irrigated trial in Fig. 5 below, although the relative size of the yield response was much lower (<15%). In this site the lint yield response to K application alone represented an 8% increase (214 kg lint/ha), but addition of P alone slightly exceeded that response (11% increase, or 284 kg lint/ha) and was not statistically different to the combined effect of P and K (12% increase, or 326 kg lint/ha).

In both examples the chance of achieving a significant yield response to an individual nutrient (typically the focus of most of the trials in this program) could often be negated by the background application of the other nutrient (e.g. P in a K trial) as part of the experimental protocols.

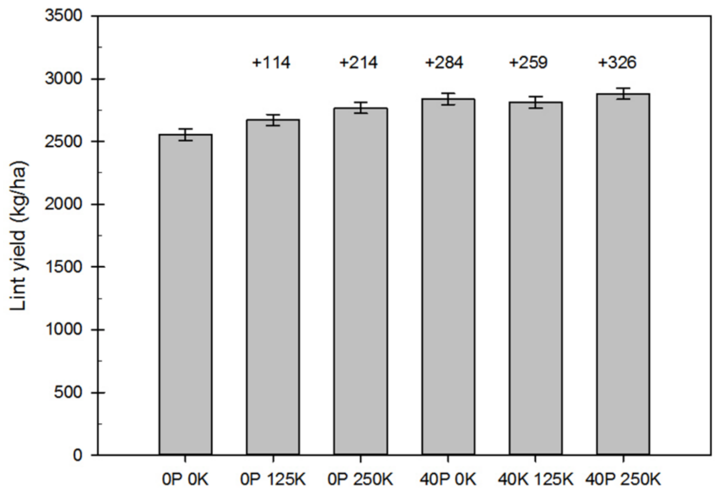
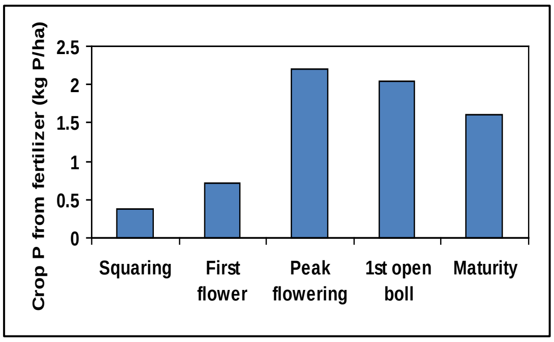



**Figure 5.** Lint yield response to various rates and combinations of P and K fertilizers in a flood irrigated cotton crop in 2014/15 season.

What was particularly interesting in the irrigated trial in Fig. 5 was that while the impact of P application on crop P uptake was relatively small (~3 kg P/ha out of 40 kg P/ha applied - consistent with other trials), it was associated with an improvement in K acquisition that was as effective as the highest K application rate alone (i.e. an additional 14-17 kg crop K uptake/ha). Interestingly, while the addition of P with K provided little additional benefit, the small relative yield response arising from that additional K uptake was still consistent with the benchmark of 5.2-5.4 kg K/100 kg lint yield) derived from the core site and shown in Fig. 4 (i.e. ~300 kg extra lint produced for the extra 14-17 kg K uptake). This efficient use of additional K uptake, despite the site exhibiting a K index of 6.6 (Table 2 - slightly above that suggested as indicating strong K responses) questions whether further yield responses could have been achieved if more efficient uptake of the applied K had been achieved.

The observation of P application resulting in increased crop accumulation of K in crop biomass has occasionally been observed in other trials in this project, but is more common in companion work being conducted in dryland grains systems. The reciprocal of that phenomenon (i.e. K fertilization resulting in increased P acquisition) has not been observed. The extent to which basal P applications have confounded the results of trials to determine the extent of K limitation in different trial sites cannot be determined, but future work needs to consider these P-K interactions.

The key finding from the field program has been the consistently poor crop recovery of applied P and K fertilizers, even in situations where crop demand is high (irrigated situations), soil reserves low and crop uptake relatively poor by published standards. This poor crop recovery suggests either a problem with the application method or something limiting root activity in the fertilized zone (the hill in irrigated systems or the top 10-20cm of the soil profile in dryland). Findings in relation to the former are discussed in the next section, but sequential sampling during the growing season undertaken at a number of the irrigated trial sites has shown that of the limited uptake that does occur, most happens early in the growing season (e.g. Fig 6), with little fertilizer P or K acquired during the period of rapid biomass and nutrient accumulation in the post flowering period. This contrasts strongly with observations from dryland cereal crops and suggests that if there is a problem with root systems in the fertilized zone it seems to be occurring from flowering onwards in irrigated crops. We have collected less sequential sampling data in dryland crops, but in the recent joint investigation with Brendan Griffiths (UNE1501) it has been shown that uptake from fertilizer-enriched topsoil layers continued for a longer period and resulted in much greater P uptake from fertilized layers than was achieved in any of our trials. The dynamics of P uptake will be presented in detail in Brendan's report in 2016, while the ability of cotton to exploit fertilizer-enriched soil layers for both P and K is covered in the next section of this report.



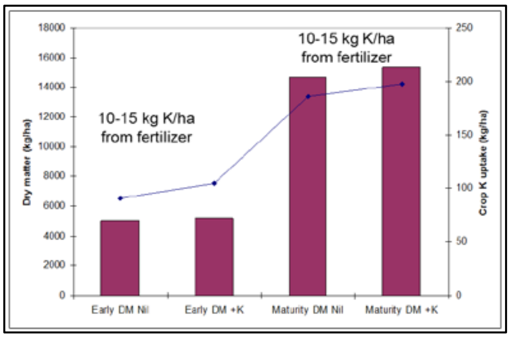




**Figure 6.** Uptake of fertilizer P and K at different growth stages in irrigated cotton grown at sites near Goondiwindi and on the Darling Downs, in crops with yield potentials of 12-14 bales/ha.

*4.2 Guidelines for effective P and K application strategies*

Under this objective we explored the ability of cotton crops to access fertilizer P and K from soil when it was (i) the result of accumulation throughout cultivated layers as a result of long term fertilizer history (Colonsay and Kingaroy); (ii) when it was fertilizer applied to the soil profile preseason as bands (at various spacings towards the base of the hill in irrigated systems and at ~20cm depth in dryland) or applied to the soil surface and incorporated with tillage during land preparation and bed formation; and (iii) when applied as foliar applications between flowering and first open boll, as supplement to soil applications.

These trials clearly showed that the most effective way of allowing the crop to access P or K was through dispersing the nutrient through a volume of soil (e.g. a 10-20cm layer) where roots were active for an extended period during the growing season. This is best illustrated by the data from Colonsay (P dispersed primarily through the 0-10cm layer in a dryland cropping area in a season with frequent, but not excessive, rainfall events in the critical period for nutrient uptake) and Kingaroy (K dispersed primarily through the top 10cm but with conventional tillage ensuring some enrichment of the 10-20cm layer and supplementary overhead irrigation ensuring good root activity), which are shown in Figure 7. These data clearly show effectively linear increases in crop nutrient uptake as the concentration of dispersed P or K in the fertilized layers increases from a low initial condition, with that trend continuing (especially for the 0-30cm profile layer) across the whole data set at Colonsay but clearly showing a plateau in each season at Kingaroy. The quantum of increased uptake was 15-20 kg P/ha at Colonsay and 50-100 kg K/ha at Kingaroy, depending on seasonal conditions. These results contrast starkly with the maximum recoveries of 2-3 kg P/ha and 10-15 kg K/ha in the field trials conducted in UQ1302 and UQ00058, and in the case of P in particular, the relatively low nutrient indices (kg uptake/100 kg lint produced) at most of the trial sites suggested this was not due to poor site selection.

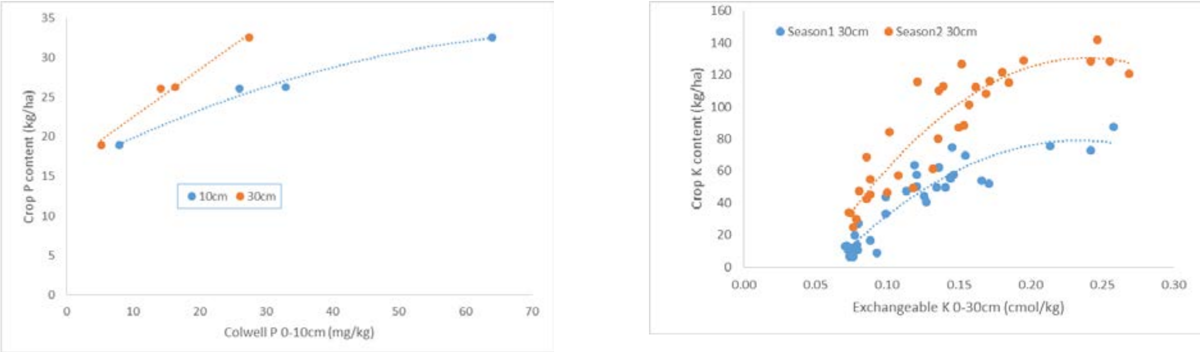



**Figure 7.** Maximum crop uptake of P and K in response to variation in soil nutrient status at Colonsay (P) and Kingaroy (K). In both situations nutrients were dispersed throughout the topsoil (0-10cm primarily at Colonsay, and the 0-10cm and 10-20cm layers primarily at Kingaroy).

The Colonsay dataset allowed a test of the effectiveness of banded P in soils with variable soil P backgrounds and where increased (dispersed) available P clearly resulted in increased crop uptake. This comparison effectively showed no significant additional crop P uptake from the bands placed 50cm apart at 20cm depth in the soil profile for the subset of treatments sampled in UNE1501, although an analysis of the yield response across the whole trial did suggest some relatively small yield responses – especially in soils where the response to additional dispersed P in the top 10cm had effectively ceased (Fig. 8). This data clearly shows that cotton is very poor at utilizing banded P fertilizer, even when the soil P status is low and the crop would respond strongly to increased P acquisition. Given that much of the P applied in the Australian cotton industry is banded, this is a key finding from the project.

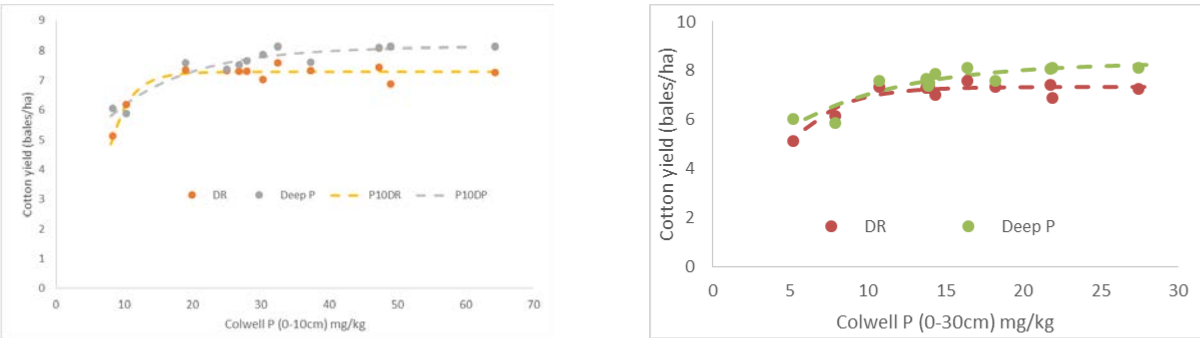



**Figure 8.** Yield response to P bands placed 50cm apart at 20cm depth in soils with contrasting background P status at Colonsay. The available P was concentrated primarily in the 0-10cm soil layer, but the relationships are plotted for a 0-10cm or a combined 0-30cm sample depth. Both sets of treatments had a common ripping treatment, with the only variable being the application of 20 kg P/ha as mono-ammonium phosphate.

The relative effectiveness of different fertilizer band spacings (25, 50 or 100cm) and band depths (in the hill or at the base of the hill) were compared to broadcasting onto the hill and incorporating with tillage in a large trial near Warra, while a second study compared different rates and application methods (banding versus broadcasting and incorporating with tillage) near Goondiwindi. Both sites were flood irrigated and yielded 12-14 bales/ha. Aside from the small differences in crop P and K uptake that were measured at about first white flower (Fig. 6), differences were negligible in later growth stages and no significant yield responses were recorded. In the Goondiwindi study soil sampling was undertaken at squaring to measure the P distribution in the hill in response to the application method (Fig. 9). Interestingly, despite the degree of soil disturbance and the initial depth of placement in the loosely tilled soil, most P and K were found in the top 15cm of the bed and it was suspected that slumping of the soil with rain and the commencement of irrigation meant that only a small fraction of the crop root zone was treated. This may have contributed to the negligible crop uptake, but the availability of moist soil in those upper bed layers would normally encourage root proliferation and nutrient uptake. The fact that it didn't, even during periods of peak nutrient demand, suggests limited root activity in the hills in both these flood irrigated fields.

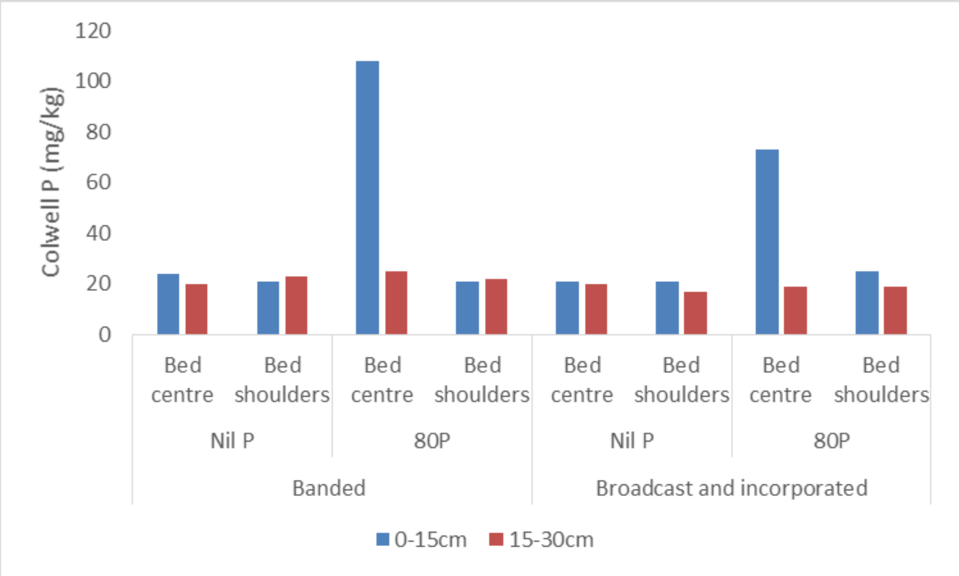
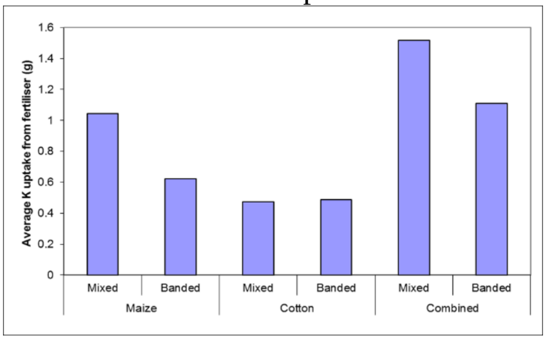



**Figure 9**. Distribution of Colwell P in the irrigation hills near Goondiwindi at squaring. Pre-planting P applications had been banded into the soil profile or dropped onto the soil surface and incorporated with tillage prior to and during bed formation. The fertilizer was applied using a commercial applicator without outlets on 100cm spacings.

The final field study of application strategies explored whether foliar applications of P or K commencing at first flowering and continuing until first open boll could complement any small increase in P and K recovery of soil-applied fertilizers and assess whether yields were P or K limited. This work was undertaken near Chinchilla on another flood irrigated property, and while the soil P and K applications had small interacting effects on crop yields (Fig. 5) but very limited impact of overall crop nutrient content, the foliar P applications (3 applications of 2 kg P/ha on each occasion) did result in small increases in crop P content of ~2 kg P/ha, or a 7% increase in overall total P content. This had no significant impact on crop yield, although visually there were suggestions of a healthier canopy during the boll ripening period and possibly a larger number of immature bolls at harvest.

Glasshouse studies with large soil cores were used to further explore the response of a cereal grain (maize) and cotton to banded or dispersed K fertilizer in soils with a variety of available K concentrations, with these studies also exploring the impact of enriching K fertilizer bands with P, or N and P, in an attempt to encourage root proliferation and improve crop K acquisition. Rubidium uptake from the K band was used as a tracer for root activity in the K band. The first sequence of experiments (shown in Fig. 10 below) had maize followed by cotton, while the reciprocal experiment (cotton followed by maize) is in mid-experiment, with the cotton about to be harvested.

Results indicated no real difference between dispersed or banded K in terms of K acquisition by cotton, and no benefits of co-locating P, or N and P, in the K band, with both findings in contrast to results for maize. Cotton was also quite inefficient at acquiring K from either bands or the dispersed treatments compared to maize, with an average of only 50% of the applied fertilizer K removed across the crop sequence and the majority of that coming in the initial maize crop. The reciprocal experiment will confirm whether these are real species differences or an artefact of the crop sequence.



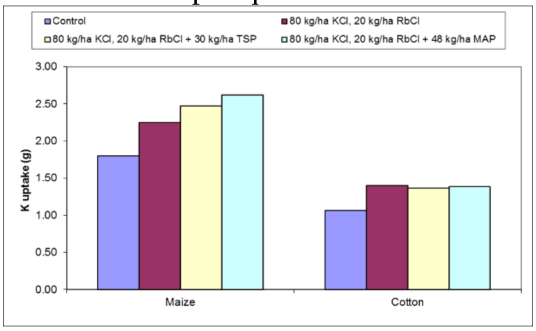




**Figure 10**. Acquisition of fertilizer K by sequential crops of maize and cotton in large soil columns in the glasshouse. Plants were grown until anthesis in maize and full flowering in cotton, and were conducted on 14 soils with a range of K statuses. Uptake of the Rubidium (Rb) tracer from the fertilizer bands was used as a tracer for root activity and allowed direct measurement of K uptake from the band rather than just using differences in K content.

In conclusion, the experimental program has conducted a variety of experiments with only a few providing real insights into how fertilizers can be used to efficiently meet the P and K requirements of cotton crops. Long term experiments (in the case of K, on an atypical soil type) have allowed calculation of internal nutrient use efficiency benchmarks (P or K uptake/100 kg lint produced). However the application of these benchmarks more broadly will require further experimental evidence to develop confidence in the robustness of these indicators for different soils and cropping systems.

A key finding from this project is the clear preference of cotton for both P and K to be dispersed through a substantial soil volume (i.e. a 10-20cm soil layer) in the active root zone up until the end of peak nutrient acquisition (typically first open boll). This represents a number of challenges for both irrigated and dryland systems. In the former, while dispersal through the hill/bed is possible with tillage during land preparation and bed formation (although perhaps requiring more aggressive methods than currently used), there seems to be a very marked decline in root activity in these fertilized layers once flood irrigation commences. This makes the crop effectively reliant on unamended subsoil layers during periods of peak nutrient acquisition and very inefficient at utilizing expensive P and K inputs, while also representing a major issue that will impact long term sustainability. In dryland systems, where fertilizer is preferentially banded to minimize disturbance and retain surface cover, we find cotton particularly inefficient at utilizing P or K from bands. Also, unlike cereal grains, the co-location of other nutrients like P and N to encourage root proliferation in and around bands seems to also be particularly ineffective in cotton.

These results suggest a clear need to re-examine the interaction between management practices (irrigation strategies, soil amendments), fertilizer placement and cotton root systems. The understandings derived from this more fundamental research will be the keys to developing more effective and efficient use of P and K fertilizers in cotton cropping systems.

*4.3 Developing a framework for crop nutrient budgeting*

Extensive monitoring of nutrient removal in cotton seed has been undertaken across all trials, but only a small fraction of those trials also had lint analysed because of a general perception of most nutrient being in the seed rather than the lint. This has been an error, as the data we have so far suggest the K in lint represents ~1/3 of the total K removal in the harvested product, although the P content is a much smaller fraction. Further lint analyses are required to explore the variation in P and K concentration for both nutrients.

The removal data are summarised in Table 3 below, and expressed on the basis of removal/t of raw cotton, assuming 45% turnout. The relatively small variation in K concentration in seed is not surprising, as similar patterns of relatively stable K concentrations in grain harvested from cereal and grain legume crops have been observed in sites with wide variation in crop K status and yield responsiveness. The observed variation shown in Table 3 was primarily between sites rather than K treatments, and produced K removal rates consistent with those developed by Rochester (2007) - 3.5 kg K/bale of cotton. This agreement would seem to be fortuitous though, as Rochester's data was based on seed K concentrations alone, while as we have demonstrated in this project, lint can make a significant contribution to K removal rates. It would seem that the site on which the Rochester data was based (ACRI) enabled luxury K uptake and seed concentrations as high as 1.2-1.3% K, *ca*. 20-30% higher than anything observed in our field sites or in the long term K trial at Kingaroy (where seed K was relatively stable at 0.9%K).

**Table 3**. Concentrations of P and K recorded in lint (1 trial only) and seed cotton in the various experiments conducted in UQ1302.

| | Proportions in raw cotton | P concentration (%) | K concentration (%) |
|---|---|---|---|
| Seed | 0.55 | 0.4-0.65% | 0.9-1.10% |
| Lint | 0.45 | 0.07% | 0.45-0.5% |
| | | P removal (kg/t) | K removal (kg/t) |
| Raw cotton | Low | 2.5 | 7.0 |
| | High | 3.9 | 8.3 |

The variation in seed P concentration was somewhat less than anticipated, and in the absence of sites with strong P responses to validate these figures, should be treated with caution. Our data suggest P removals of between 1.3 and 1.9 kg P/ha/bale (assuming 45% turnout), with these values (especially the lower end of the observed seed P concentrations) substantially less than the value published by Rochester (2007) for crop budgeting purposes (2.3 kg P/bale). Either the existing benchmark data are from a crop with luxury P uptake and seed P concentrations (ACRI soils typically have high available P reserves) or, as suggested by the crop P indices derived in Table 2, our trial crops were characterised by very low P contents. The data from Colonsay (reported in UNE501) supports the contention that removal rates reported by Rochester are from crops with luxury P uptake. The low P treatments at Colonsay (Fig. 8), where yields were reduced to ~60% of $Y_{max}$, had seed P concentrations of 0.4%P, rising to ~0.50% with the highest P treatments tested. This puts these data well within the range reported for our trials in UQ1302, again suggesting that the sites on which our P research was conducted were likely constrained by inadequate P.

In grain and grain legume crops seed P concentration has been shown to vary strongly between sites, as well as with crop P status, and most of the variation shown in Table 3 was due to between site factors rather than the effect of P treatment. This may not be surprising given our relative inability to affect crop status with applied P fertilizer in most trials, and is consistent with the relatively low crop P indices shown in most of the experimental sites in Table 2. Once more P responsive experiments can be reliably established the issue of variability in seed P concentration can be explored more fully.

*4.4 Extension and development program*

The extension and development component of this project undertook a variety of activities that are reported under three main headings –

*Testing of fertilizer application strategies in on-farm strip trials*

A series of on-farm experiments was conducted in response to grower interest in the feasibility of in crop applications of P and K, and also in the effectiveness of different P and K application methods (banding v incorporation into the hill). The interest in in-crop application arose after growers had experience with top dressing in the extremely wet 2010/11 and 2011/12 seasons, when root activity deeper in the soil profile was constrained by anoxic conditions.

The trial locations and brief description of experiments are shown below -

(1) John Durham: "Neilo" Toobeah.

Soil test: 9ppm P (Colwell), BSES P 20mg/kg, Sulfur 8mg/kg, K (Amm. Ace.) 344ppm

Phosphorus application strip trial looking at spreading v banding v spreading and banding. "No significant yield response or visual"

This site should have been P responsive, and may have been affected by the lack of P uptake in the hill observed in other flood irrigated trials. No plant samples to determine crop P uptake were conducted.

(2) Micheal Josh (P & J Harris) "Glenroy" Moree.

2 trials exploring in crop application of P & K with different combinations of rates and timings for each nutrient.

"No significant response, although there appeared to be a visual response"

(3) Nathan Bradley "Bangaween" Bowenville.

2 trials exploring in crop application of P & K with different combinations of rates and timings for each nutrient.

"No significant response, although there appeared to be a visual response". No plant samples to determine crop P uptake were conducted.

(4) Patrick Hilliar "Woongarra" Jimbour.

2 trials exploring in crop application of P & K with different combinations of rates and timings for each nutrient.

"No significant response, although there appeared to be a visual response". No plant samples to determine crop P or K uptake were conducted.

(5) Stewart Leadbetter "Cabarita" Brookstead.

A K application trial consisting of 3 rates x 3 replicates.

"No significant response recorded". No plant samples to determine crop K uptake were conducted.

The same concerns regarding interpretation of these responses exist as for the field trials. All sites were flood irrigated, and so differences between rates or incorporation methods may well have been constrained by the poor root activity in the fertilized hill. Without crop uptake data it is impossible to assess the P of K status of crops against our developing benchmarks (derived from Fig. 4), but the lack of response to top dressed P or K is not surprising given the observations about the importance of incorporation into a substantial soil volume to achieve good crop access.

*Conducting an on-farm trial comparing the effectiveness of composts and other organic amendments*

This experiment had commenced prior to the beginning of UQ1302, but was continued over the 3 summer seasons (followed by a final winter wheat crop in 2015). It was a replicated strip experiment exploring the impact of three composts and 2 other uncomposted organic amendments (chicken and feedlot manures) on soil properties and crop productivity against a reference treatment of inorganic N fertilizer (the local commercial standard). The trial grew a crop of maize in the initial year (2011/12) followed by 3 consecutive cotton crops in 2012/13, 13/14 and 14/15, with the block also double cropped into winter wheat in 2015. Each amendment was applied at rates of 5 t/ha prior to each crop season (a total of 25 t/ha applied over the 5 year monitoring period. The performance of the successive cotton crops and the final wheat crop are shown in Table 4.

Statistically there were no differences in productivity between the amendments in any cotton crop, with the exception of a small advantage from the beef-derived products in the lower yielding 2013/14 season. This lack of amendment differentiation was also observed in the combined analysis across all three cotton crops, with an average advantage over the traditional synthetic N fertilizer of <2%, or 100 kg/ha raw cotton). The only amendment that was statistically different to the fertilizer reference was the composted beef manure, with that amendment conferring a 3.5% yield increase (200 kg/ha raw cotton).

Differences between treatments were slightly more pronounced in the 2015 wheat crop, and there were differences between amendments. The raw chicken manure treatment performed no differently to the fertilized control, and yielded poorly compared to all other amendments. These amendments conferred a 450 kg/ha yield increase (~10%) over the fertilized control.

Collectively, this analysis shows little productivity benefit from what was an intensive soil amendment program (25t/ha over 5 years), and suggests that the site was characterised primarily by N limitations (i.e. the application of other nutrients in the amendments provided no detectable benefits). This finding would question the value of an amendment program in this scenario. While there were some beneficial effects on soil properties (nutrient status and microbial activity) measured in the trial, these were clearly not alleviating a productivity constraint at this site.

**Table 4**. Yields of three successive cotton crops (2012/13 – 2014/15) and a final wheat crop (2015) at the long term amendment trial on the Darling Downss

| | Raw cotton yields (kg/ha) | | | | Wheat yield (kg/ha) |
|---|---|---|---|---|---|
| | 2012/13 | 2013/14 | 2014/15 | Average all years | 2015 |
| Zero Amendment + N | 5606 | 4186 | 6736 | 5510 | 4829 |
| Own compost at own rate @ 5t/ha | 5739 | 4279 | 6624 | 5547 | 5117 |
| Raw Poultry/barn Litter manure @ 5 t/ha | 5601 | 4258 | 6787 | 5548 | 4827 |
| Composted poultry/barn litter @ 5 t/ha | 5871 | 4365 | 6760 | 5665 | 5393 |
| Raw Beef manure @ 5 t/ha | 5743 | 4529 | 6535 | 5602 | 5433 |
| Composted beef manure @ 5 t/ha | 5587 | 4500 | 7038 | 5709 | 5208 |
| Lsd (P<0.05) | ns | 178 | ns | 187 | 383 |

While there were few statistically significant changes in soil chemical properties between amendments, or between amendments and the fertilized control, some examples of properties that did show significant differences (Colwell P and DTPA Zn) are shown in Fig. 10 for the 0-10cm and 10-30cm layers. Clearly most of the benefits were observed in the top 10cm, and in this layer there was also an increase in plant available K of ~10% relative to the fertilized control (i.e. 0.90 v’s 0.84 cmol/kg). The relevance of this layer to crop nutrient acquisition of immobile nutrients like P, K and Zn in flood irrigated cotton (as on this property) has been shown to be questionable in work conducted in the field trial program, so the lack of impact on crop productivity is probably not surprising. Interestingly, the greatest responses were shown in the final wheat crop, which has been

shown to be able to exploit nutrient enriched bands and layers, provided moisture is available.
Assessments of the impact of amendments on soil biota were also conducted, with greater differentiation between amendments than in yield or soil fertility parameters. In these assessments the locally produced farm compost derived from gin trash was not significantly different to the fertilized control, but amendments of composted beef and chicken manures resulted in increases in $CO_2$ emissions (an indicator of general microbial activity) of ~60% relative to the fertilized control.

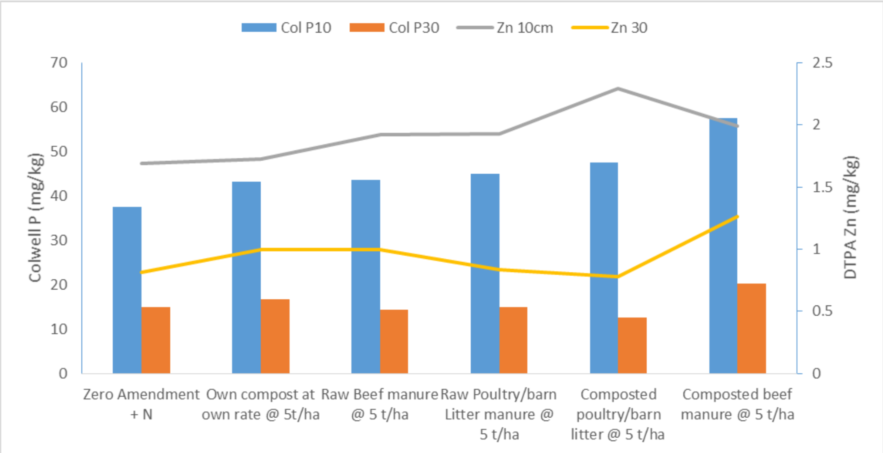



**Figure 10**. Impact of 5 years of application of organic amendments (a total of 25 t/ha) on concentrations of plant available P (Colwell P, mg/kg) and Zn (DTPA-extractable Zn, mg/kg) in the 0-10cm and 10-30cm layers of the soil profile. The clear stratification of these immobile nutrients is evident in the top 10cm of the profile.

*Coordinating extension & development for crop nutrition and nutrient management issues in the cotton industry*.

A significant level of industry engagement was undertaken by researchers and extension staff throughout the project. This engagement occurred at all levels throughout the industry from individual discussions with growers and consultants, group field walks and field day presentations, grower group meetings, regional crop nutrition training, consultancy meetings, industry seminars and conferences. A particular focus was on the role of deep placement of P and K (as per grains cropping systems) and on improving nitrogen use efficiency.
This engagement was supported by numerous articles in publications such as Spotlight, Australian Cotton Grower, Cotton Production Manual and the Cotton Symptoms Guide, supported by case studies, grower notes and conference posters. In addition, the nutrition module in myBMP was reviewed and updated to include the latest research and relevant research outcomes. Nutripak has been reviewed and is presently in a position to be revised and updated.
Important relationships were developed with key industry organisations, service providers and government agencies, opening good communication channels and allowing research outcomes in information to be regularly and easily delivered and feedback received. Key relationships were developed with crop consultants, the Cotton Info team, various cotton grower groups and other key researchers and research institutions.
There were several key foci for extension delivered throughout the project. These were (1) the monitoring and management of macronutrients (phosphorus, potassium and sulphur) in cotton cropping systems, including soil and plant sampling strategies, monitoring and assessment of crop performance, determining appropriate rates and application strategies for each nutrient, and understanding the longer term impacts of nutrient applications on plant available nutrient status and the sustainability of land management systems.

(2) Keeping up to date with the latest research outcomes, interpreting the key findings and promoting their application to cotton systems
(3) Promoting the benefits of the 4R's of nutrient management (right product, right rate, right placement and right timing) in cotton farming systems. This is particularly relevant to immobile (but highly residual) nutrients like P and K, where an understanding of nutrient behaviour in the soil and dynamics of plant uptake are essential.
(4) The project also provided extension support on crop nutrition and soil management to growers in the Burnett following the devastating floods in 2014. It was also able to provide input and comment into the development of the Qld State Government response to the Federal Carbon Farming Initiative and the development of the Qld Governments Strategic Cropping Lands initiative.

***Outcomes***

**5. Describe how the project's outputs will contribute to the planned outcomes identified in the project application. Describe the planned outcomes achieved to date.**

The planned project outcomes were focussed on developing improved guidelines for deciding on the need for P, K and S fertilizers in the cotton farming system and testing the various fertilizer application strategies to optimize crop recovery and use efficiency. Collectively it was intended that these outcomes complement the work on N management in cotton and broader nutrient management in the grains industry, allowing the development of nutrient management guidelines that can be implemented across the whole cropping system in northern Australia, where cotton and grains are often grown in rotation. These guidelines were to be supported by regional testing of recommendations on commercial properties, in collaboration with development/extension officers, consultants and growers. Project staff were to lead the development of extension material and participate in industry workshops.
While not able to develop widely applicable and ready to use guidelines for the targeted nutrients, the project has made a number of very important contributions towards improving P and K management. These include -

(i) Clearly demonstrating the current inefficient use of P and K in cotton crops, both irrigated and dryland. This inefficiency has created considerable uncertainty around the extent to which yields in both dryland and irrigated cotton crops are constrained by inadequate nutrient supply, as a lack of yield response to applied fertilizer that was not able to be acquired by the plant provides no guidance as to the extent of any yield constraint or fertilizer response. In short, fertilizer test strips established using current application strategies are quite likely uninformative.

(ii) Developing tentative frameworks that allow benchmarking of crop yields against crop nutrient uptake, and providing an indicator of possible crop nutrient status. While in early days, data from this benchmarking has suggested that while suboptimal crop P status characterises many crops in this region, limited availability or uptake of K is much less common (despite the widespread use of K fertilizers).

(iii) Banded applications of P (and to a lesser extent K, depending on soil type) have been shown to be an extremely inefficient way of applying these nutrients to achieve crop recovery, with the crop seemingly unable to proliferate enough roots in nutrient-enriched zones around bands to enable good nutrient recovery. Changing the blend of nutrients in the band also seems to have little impact on crop recovery. The contrast with cereal crops is marked, and the optimal strategy for cereals may be quite different to that of cotton in the same cropping system. This represents particular challenges for dryland cropping, where aggressive tillage options are limited by a desire to retain surface cover to maximise soil water storage.

(iv) Identification of what appear to be real problems with maintaining cotton root system activity in the upper profile layers (where immobile nutrients are concentrated) under flood irrigated management systems. This will increasingly become a sustainability issue as subsoil P and K reserves are eroded further by crop uptake. Solutions will involve either drastically modified fertilizer application strategies (to achieve dispersed nutrients in a large soil volume below the irrigation hill) or improved use of soil ameliorants and/or modified irrigation methods. Further detailed study of the interaction between cotton root system activity, nutrient placement and soil water dynamics are required to resolve these issues before more extensive field research can productively recommence.

(v) Clearly demonstrating the relative ineffectiveness of foliar P and K applications as a means of overcoming a crop nutrient deficiency. The limited uptake of these foliar applied macronutrients and the frequent field operations required to apply a large enough quantity to achieve a detectable change in nutrient status mean this strategy should not be supported, with the possible exception of a short term salvage strategy after a severe waterlogging event.

(vi) The project has provided some verification of the rates of K removal in seed and lint used for nutrient budgeting, but cast some doubt on the removal rates of P. The high P removal rates published by Rochester (2007) may be a result of luxury crop uptake and partitioning to seed in a high P soil (ACRI), and further analysis of the extent of variation in seed P concentrations in response to both soil type and crop P status are required to develop realistic budgeting strategies.

(vii) An additional outcome of this project was the demonstration of the relatively limited benefits obtained from the use of organic amendments in cotton fields, compared to traditional synthetic fertilizers. While soil nutrient content (especially P and Zn, and to a lesser extent K) could be boosted with a quite intensive regime of soil amendment application (25 t/ha in 5 crop years), the response in crop performance was limited. These conclusions are limited to the site on which the work was conducted, but should provide a reality check for what soil organic amendment use can and can't deliver.

(viii) Collectively, the improved understanding of the interactions between management practices and P and K fertilizers and the impact of long term use of organic amendments will provide useful insights to industry and advisors. This will be achieved by Mr Weir undertaking to ensure that the nutrition module in myBMP and Nutripak are updated with this latest information.

**6. Please describe any:-**

**a) technical advances achieved (eg commercially significant developments, patents applied for or granted licenses, etc.);**

NA

**b) other information developed from research (eg discoveries in methodology, equipment design, etc.); and**

NA

**c) required changes to the Intellectual Property register.**

NA

***Conclusion***

**7. Provide an assessment of the likely impact of the results and conclusions of the research project for the cotton industry. What are the take home messages?**

Management of immobile nutrients like P and K represents a major challenge to the sustainable management of soils supporting the Australian cotton industry. In particular, the inability of cotton crops to efficiently recover applied P and K fertilizer, even when soil moisture availability is not limiting (ie. under irrigation), suggests serious attention needs to be paid to the functionality of cotton root systems, and the interactions of root system function with soil water dynamics. The observation of an almost complete cessation of nutrient acquisition from the hill from the beginning of the rapid nutrient accumulation period after first flower under flood irrigation means current application strategies are ineffective and fertilizer use efficiency extremely poor. This will become an increasingly important issue as indigenous subsoil reserves are depleted and the crop is increasingly dependent on applied fertilizer for nutrient supply.

Our research has clearly shown that banding P fertilizer is an inappropriate application strategy for cotton, which is extremely poor at utilizing concentrated sources of P. There are similar indications for application of K, although further work on low K soils with strong K buffering characteristics (high CEC) or poor soil structure (sodicity) is required to explore the trade-offs from enhanced diffusive supply from a high concentration band versus limited root access to K-enriched soil. There seems to be little benefit from nutrient co-location in the band to improve root proliferation, in contrast to other grain crops in the cotton rotation.

The implications of these findings represent a significant challenge for cotton farming systems. As our trials demonstrated, simply broadcasting P and K onto the soil and incorporating using standard tillage and bed forming equipment does not achieve the degree of mixing required to have a major impact on the volume of enriched soil accessible to roots. The challenge of enriching an even larger soil volume to improve crop P and K uptake suggests tillage will remain an important facet of an effective fertilizer application strategy. However this approach is difficult to reconcile with the farming systems benefits derived from conservation tillage systems (especially under rainfed conditions), where the benefits of reduced tillage, permanent beds and stubble retention are increasingly apparent for water use efficiency, soil carbon sequestration and soil health considerations.

The Australian cotton industry needs to support fundamental studies into enhancing the effectiveness of cotton root systems in response to various challenges in the farming system (flood irrigation, poor soil structure), including consideration of the extent to which current genotypes are a contributing factor. As noted in the recent paper by Hallugalle *et al.* (2015), the current transgenic cotton varieties would appear to have a less extensive root system than their conventional predecessors. Therefore, the extent to which breeding/varietal selection can contribute to a solution to the problem of poor nutrient acquisition needs to be considered.

***Extension Opportunities***

**8. Detail a plan for the activities or other steps that may be taken:**

**(a) to further develop or to exploit the project technology.**

(i) There is a need for ongoing education and training programs developed around macronutrient management and farm-specific nutrient monitoring and fertiliser programs. In particular, this needs to focus on application strategies for P and K and on further developing indicators of crop P and K status.

(ii) The second iteration of the cotton-maize K placement experiment with large soil columns is mid-sequence at the time of writing this report. After cotton harvest, maize will be sown in the New Year, and the combined analysis will then allow unconfounded assessments of response to K bands on soils with different K status and background CEC, and on the impact of co-location of N and P with K to encourage root proliferation.

**(b) for the future presentation and dissemination of the project outcomes.**

(i) The industry is hearing potentially conflicting results from IPL/UNE1501 (regarding strong P responses at Colonsay) and from UQ1302 (poor recovery of applied P and K and a lack of crop response). The integrated analysis of the two sets of data in this report has provided a clear and logical explanation for what is happening and why. This integrated message needs to be presented to industry, preferably in joint presentations by Bell/Lester and Griffiths in appropriate forums.

(ii) The industry also needs to be briefed on the findings of the Soil Organic Amendment Trial, so that expectations around the use of these materials can be tempered by a realistic assessment of what they can and can't achieve. Another key learning will be to ensure a focus on the aspects of nutrition these materials are likely to impact (i.e. in season N mineralization and a reduced fertilizer N requirement, as well as P, K, S and Zn) and how to identify soisl and systems where these benefits might be realized.

(iii) Finally, there are a number of technical papers that are in various stages of preparation for submission to journals, and others (for example, the integration of the Colonsay and UQ1302 field work) that are being planned.

**(c) for future research.**

(i) Detailed research to explore root system function in response to different irrigation regimes and soil moisture dynamics. In particular, the impact of soil and irrigation management on the frequency of oxygen-limiting/waterlogging events and root function will be a key focus.

(ii) Genotypic variation in the ability to exploit heterogeneously distributed nutrient patches should also be a focus of future research.

## 9. A. List the publications arising from the research project and/or a publication plan.

The project has been involved in a number of technical and industry-focussed publications, as well as presenting to industry and consultant-focussed workshops on research outcomes. The key publications and events are listed below.

**Technical conferences:**

Mike Bell, Chris Guppy, Phil Moody (2014). Nutrient inputs other than nitrogen in cotton systems – some observations and perspectives. Pp. 15-18. Proc. 17th Australian Cotton Conference, Gold Coast.

David Lester, Mike Bell and Duncan Weir (2014). Phosphorus, potassium and cotton – where are we up to? Pp. 37-39. Proc. 17th Australian Cotton Conference, Gold Coast.

Michael Bell and David Lester (2015). Cotton root systems and poor recovery of P and K fertilizers. Proceedings, 9th Symposium for the International Society of Root Research, Canberra. 6-9 October 2015.

David Lester, Peter Want, Lawrence Smith, Mike Bell (2015). Cotton picker trials & adjustments…Proceedings, 2015 Cotton research conference, Toowoomba.

Peter Want, David Lester, Mike Bell (2015). From field to laboratory. Proceedings, 2015 Cotton research conference, Toowoomba.

David Lester, Mike Bell (2015). Cotton root systems and recovery of applied P and K fertilisers. Proceedings, 2015 Cotton research conference, Toowoomba.

**Industry reference material:**

Cotton Info Web Site: Soil Health Crop Nutrition. Cotton Symptoms Guide: Chapter 5 (Soil constraints and planting management) and Chapter 7 (Nutrient deficiencies/toxicities).

http://cottoninfo.com.au/publications/cotton-symptoms-guide

D Weir and I Rochester (2013). Nutrition Efficiency - Nutrients and soil constraints that impact cotton. Australian Cotton Production Manual pp. 33-39.

D Weir (2014). Soil health case study – Improving soil health using compost manure. http://cottoninfo.com.au/publications/soil-health-case-study-improving-soil-health-using-compost-manure

**Industry articles and media:**

D Weir (2012-2015). Australian Cotton Grower: Regional Report for the Darling Downs (every publication)

M. Bell, D Lester, D Weir (2014). Fertilizer management research. Article in Spotlight in Summer 2014. http://www.crdc.com.au/sites/default/files/pdf/Summer14-15_Web.pdf

Nutrition Efficiency.docx

Bell et al_P and K in cotton Roots symposi


**B. Have you developed any online resources and what is the website address?**

NA

## *Part 4 – Final Report Executive Summary*


Current nutrient management strategies are based primarily on the concept of cost effective nutrient management (i.e. deriving an economic return from fertilizer investment), unless managers have consciously embarked on a nutrient replacement approach to balance crop nutrient removal. The consequence of cost effective strategies is that soil fertility reserves of (originally) non-limiting nutrients will decline until fertilizer applications become warranted. Soil testing has shown that reserves of P, K and S have been gradually declining but there is little definitive evidence of the threshold soil test values which indicate when fertilizer application becomes warranted. This is particularly so for the alkaline cracking clay soils that support the Australian cotton industry. In addition to the lack of clear guidelines to identify fertilizer responsive field sites, there is also uncertainty surrounding the most effective fertilizer application strategies (rates, placement and timing) to allow efficient crop recovery and use. These issues are particularly important for immobile nutrients which don’t redistribute down the soil profile as moisture profiles refill.

This project undertook an extensive field research program to improve the soil testing guidelines for defining P and K responsiveness in irrigated and dryland cotton systems and to evaluate fertilizer application strategies (soil or foliar applications, fertilizer banding or incorporation) in terms of crop recovery and crop response. Both these nutrients already figure prominently in cotton fertilizer programs.

The key research findings have been that the efficiency of use of applied P and K fertilizers in most cotton farms is extremely poor, due to a combination of a crop root system that exploits fertilizer bands poorly and a phenomenon observed in flood irrigated systems where root activity in the fertilized hill declines rapidly once irrigation commences. If P and K are dispersed through a soil volume where adequate cotton roots are active during peak uptake periods (from first flower to first open boll), the crop can accumulate substantial quantities of both nutrients – even to the extent of clear luxury uptake. However the predominance of banded applications in dryland systems (to facilitate rainfall capture and storage) and the phenomenon of poor utilization of nutrients from the bed after flowering under flood irrigation are combining to seriously restrict nutrient use efficiency. Foliar applications of P and K were not an effective strategy to address these constraints.

The implications for productivity in the broader industry are uncertain, as the lack of recovery of applied fertilizer in most field trials has prevented meaningful interpretations of the degree of P or K constraint evident at each site. We have derived indices (kg nutrient uptake/100 kg lint yield) from long term experiments where P and K responses are substantial to attempt to benchmark crop nutrient status in the regions where research was undertaken. While preliminary, these indices suggest relatively widespread evidence of low-marginal crop P status in NNSW and southern Queensland, but less frequent occurrence of low crop K. While these benchmarks may not easy to adopt more broadly, we have also explored seed nutrient concentration as a possible indicator of crop P and K status. Considerable variation in seed P concentration is evident, but little for seed K. While important for nutrient budgeting calculations, seed P analyses may ultimately offer a more practical way of benchmarking crop P status.

While an improved understanding of the apparent impaired shallow root activity in flood systems is being developed, the irrigated industry should clearly move from banded to dispersed (broadcast and incorporated with tillage) P and K applications, with the depth and thoroughness of the incorporation a key to improving nutrient recovery. In dryland situations the solutions are less clear, but it is apparent that greater efficiencies of P and K recovery can be achieved by the grains crops grown in rotation with cotton than by cotton itself. The most effective interim strategy may be to allow the cotton crop to exploit residual (and potentially more dispersed) fertilizer residues and utilize the post-cotton pupae busting tillage operations as the opportunity to apply most P and K fertilizer in the crop rotation.