What is cotton's sustainable yield potential?

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In 1969, Don Baker and John Hesketh of the University of Mississippi calculated that the maximum yield potential of cotton was 19.1 bales per hectare. This value was estimated by using leaf photosynthesis and respiration data from their experiments in the years up to 1969.

The value seemed relatively high at that time as Australian cotton yields between 1964 and 1969 averaged 4.2 bales per hectare — higher than those achieved in the US at the same time.

So an estimate of yield potential that was 4.5 times higher than commercial yields indicated there was either substantial capacity to increase commercial yields and/or that using leaf photosynthesis measurements overestimates yield potential.

Australian cotton yields have been steadily increasing over the past 20 years at a rate of about 0.1 bales per hectare each year. By comparing yield of old varieties grown today against current varieties, and comparing with yield in the past, we can measure quite accurately that 45 per cent of this increase in yield is due to better yielding varieties. The other 55 per cent is due to better crop husbandry (for example, soil, water and insect management).

In 2004–05, there are many reports of very high yields at the field level, with up to 15 bales per hectare recorded, and farm and regional yields exceeding 10 bales per hectare. Australia's average irrigated yield for the 2005 harvest was 9.7 bales per hectare, a new record.

Some yields in 2004–05 got within striking distance of the theoretical maximum.

SUMMARY

In this article we investigate cotton's yield potential and explore a number of issues involved and constraints in achieving this. We found that:

- Maximum yield potential of cotton appears to be around 19 bales per hectare, assuming no stress, perfect sunshine and using the peak values for boll growth rates that have been measured. This agrees with early US work by Baker and Hesketh;
- Yields of 15 bales per hectare require 170 bolls per metre at two gm of lint per boll; a big crop with a high harvest index (greater than 20 per cent); 10–14 fruiting branches per plant; N removal of 195 kg per hectare; replacement of phosphorous and potassium levels; and, 12 ML of irrigation water pumped (assuming 1.25 bales per ML);
- Higher water and nutrient use efficiency appear to be keys to sustainable high yields. Higher yields may require maintaining high crop growth rates for longer; increasing the duration of functional green leaf area; and higher harvest index.

With market competition and prices as they are, our cotton growing businesses need higher yields to maintain profitability.

So we now have yields in the field that are 80 per cent of the potential yield estimated by Don and John in 1969. As part of our agronomic and breeding strategic research planning, we thought it worthwhile to revisit the subject of yield potential.

It may be that Don and John underestimated the yield potential — in that case we can expect our best yields will continue to increase as long as the crop resource demands can be met. On the other hand, if Don and John overestimated yield potential, then yields cannot continue increasing indefinitely and we should instigate research to enable high and/or more efficient yields for future cropping systems.

MAXIMUM YIELD POTENTIAL REVISITED

In our reanalysis of cotton's potential yield we used three approaches (see below).

The first approach estimated yield from our current knowledge of boll growth rates and the duration of the boll growth period.

The second estimated yield using measurements of radiation use efficiency (the amount of dry matter produced by the plant per unit of light intercepted).

Both of these analyses assume that there are no impacts on crop growth (and fruit retention) by disease, insects, drought, waterlogging and temperature.

The final approach used the OZCOT cotton crop simulation model, where we removed the effects of various stresses in the model that limit crop growth to see what the highest simulated yield might be.

Boll growth rates

We took typical boll growth and explored the impact of increasing boll growth using known measurements of photosynthesis under ideal conditions. Maximum boll growth rates have been recently measured in the field ranging from 17 to 20 grams per square metre per day (Bange, Milroy and Yeates). Estimates by Greg Constable in ideal conditions generated growth rates of 25 grams per square metre per day (an increase of approximately 20 per cent over field measured values). We also explored the impact of increasing the duration of boll growth period (Figure 1).

The results of this analysis showed that high yields are a result of growth rates reaching around 20 grams per square metre per day, and boll growth periods of at least 90 days (Table 1). The boll growth period is the period over which the crop sets and develops bolls, not the time taken for a boll to develop. A potential yield of 19 bales per hectare can be achieved by increasing boll growth rates to 25 grams per square metre per day and extending the boll growth period beyond 90 days.

Radiation use efficiency

The second approach used to estimate yield was by using the measured average

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maximum seasonal field radiation use efficiency (RUE). This value of RUE was measured at 0.66 grams of plant dry matter for each MegaJoule of intercepted sunlight.

We approximated the light interception by a crop using known growth patterns of leaf area dynamics and the crop canopy's ability to intercept light. We applied these relationships to measurements of solar radiation for Narrabri assuming no cloudy conditions.

For a long season in north west NSW using a RUE of 0.66 grams per MJ, we were able to estimate a yield of 17.8 bales per hectare. To achieve a potential yield of 19 bales per hectare only requires an eight per cent increase of RUE to 0.71 grams per MJ — certainly possible because some measured values of RUE have been as high as 0.96 grams per MJ.

OZCOT

Similar results (18.1 bales per hectare) were achieved using the cotton crop simulation model OZCOT by removing all stresses (particularly waterlogging, limited water and nitrogen stress). The simulation used solar radiation data assuming no cloudy conditions and setting maximum daily temperature to a constant 30°C and minimum daily temperature to 20°C.

WHAT DOES IT MEAN?

The photosynthetic rates of modern varieties are only a fraction better than those of older varieties, so in summary Don and John were about right. In fact it is necessary to maintain high growth rates for boll filling periods of at least 100 days in order to achieve yields of 19 bales per hectare or more.

TABLE 1: Estimated potential yield (bales per hectare and per acres in brackets) utilising maximum boll growth rate and boll growth period

Crop boll growth period (days)	Peak boll growth rates (grams/m^2/day) 20	25	30
70	10.5 (4.2)	13.2 (5.3)	15.4 (6.2)
90	13.2 (5.3)	16.5 (6.7)	20.3 (8.2)
110	16.3 (6.6)	20.2 (8.2)	24.5 (9.9)

FIGURE 1: An example of the boll growth rate curves used to estimate cotton potential yield

Higher yields are achieved by raising the maximum boll growth rate or extending the boll growth period (period over which the crop will set and fill bolls)

It was clear from these calculations that 19 bales per hectare yields need every day to be near perfect for crop growth in terms of temperature, sunshine, nutrition and water.

What does a 15+ bale per hectare crop need?

Approaching this subject from another angle is to calculate what must happen for yields of 15 bales per hectare or more to be achieved. Table 2 shows a comparison of some plant growth, nutrient and water requirements for yields of 7.5, 15 and 20 bales per hectare. These calculations show that:

- Boll numbers for yields of 15 bales per hectare are achievable — it is necessary to actually harvest and gin 170 bolls per metre at an average size of two grams of lint for each boll (current boll sizes range between about 1.5–2.5 grams of lint per boll).
- Plant growth of 2270 grams of dry weight per metre for 15 bales per hectare is very high and difficult to achieve. Instead it is probably necessary to increase the crop's harvest index (the lint yield as a proportion of total growth) to 20 per cent or more to achieve higher yields rather than just increasing plant size. Increases in harvest index can sometimes be achieved by increasing retention, boll size and gin-turnout percentage, or all of these together.
- Boll producing fruiting branches of 10 to 14 per plant (17 to 21 total main-stem nodes) are required. This is commonplace commercially and fruiting

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branch numbers would not appear to be a constraint for 15 bales per hectare.

- Nitrogen removal is 195 kg N per hectare for a 15 bales per hectare crop. This is a high value, even for a replacement fertiliser program. If N use efficiency (that is, yield per unit of fertiliser; analogous to better harvest index) could be improved, then soil nutrient depletion would be reduced. In the example given, if N removal was decreased from 13 kg N per bale to 10 kg N per bale, N removal would be reduced to 150 kg N per hectare.
- Phosphorus and potassium removal of 32 to 50 kg per hectare respectively for a 15 bales per hectare crop. These are significant amounts and an important consideration in replacement fertiliser programs. NutriPAK and NutriLOGIC are currently being updated to include estimates of nutrient replacement requirements for high yielding crops.
- Pumping 12 Ml per hectare to achieve 15 bales per hectare with 75 per cent irrigation efficiency and 1.25 bales per Ml water use efficiency are significant challenges. In fact, much higher water use efficiency is required (up to two Ml per hectare) to allow efficient high yields and it may be that high yields and better efficiency go hand in hand (note bold values on a diagonal in Table 2). Good fallow moisture use, some effective rain and higher irrigation efficiency and water use efficiency would be required to reduce the pumping volume to less than nine Ml per hectare. It is important to consider the need to balance crop area, water availability and yield per hectare to optimise yield for a farm enterprise.

TABLE 2: Calculated plant growth, nutrition and water requirements for yields of 7.5, 15 and 20 bales per hectare

Crop variable		Realised yield		
bales per hectare		**7.5**	**15.0**	**20.0**
bales/ac		3.0	6.1	8.1
kg lint/ha		1703	3405	4540
bolls/m	at (2 g lint/boll)	85	170	227
Dry weight/m^2 at harvest index of:	15%	1135	2270	3027
	20%	851	1703	2270
Fruiting nodes at 2.5 sites/node and at retention of:	50%	6.8	13.6	18.2
	60%	5.7	11.4	15.1
	70%	4.9	9.7	13.0
N removal/ha	13 kg N/bale	98	195	260
	10 kg N/bale	75	150	200
K removal/ha	3.3 kg K/bale	25	50	66
P removal/ha	2.1 kg P/bale	16	32	42
Crop water use (ML/ha)	at 1.25 b/ML	6.0	12.0	16.0
	at 1.5 b/ML	5.0	10.0	13.3
	at 2.0 b/ML	3.8	7.5	10.0
Irrigation water applied (after 1 Ml stored; 2Ml rain)	at 1.25 b/ML	3.0	9.0	13.0
	at 1.5 b/ML	2.0	7.0	10.3
	at 2.0 b/ML	0.8	4.5	7.0
Irrigation water needed pumped at 75% irrigation efficiency	at 1.25 b/ML	4.0	12.0	17.3
	at 1.5 b/ML	2.7	9.3	13.8
	at 2.0 b/ML	1.0	6.0	9.3

CONCLUSIONS

Our calculations indicate that there is still room to increase yield before we hit the maximum yield potential. The highest yields require crops with high rates of boll growth, long period of boll set and development, high radiation use efficiency, little stress and perfect weather.

Yields of 15 bales per hectare or more require large plants with efficiency in crop harvest index, nutrition and water delivery and use. Excellent soil quality (especially crop rotation and min till) and fertiliser programs would facilitate these efficiencies. Super yields would require further improvements in efficiencies. Clearly our modern production system and high yield expectations are pushing the capacity of cotton's growth potential.

With our national average near 10 bales per hectare, there are many fields below this level to work on to increase our average. There may also be significant opportunities for research to enhance yields. Our reanalysis shows that increased yield may be attained by:

- Maintaining crop growth rates (increasing photosynthesis/reducing respiration) and/or duration of functional green leaf area;
- Increasing harvest index;
- Reducing the impacts of abiotic stress (for example, high temperature, waterlogging); or,
- Improving nutrient uptake (for example, through improving soil quality, fertiliser types) and water use efficiency.

Our current research and decision support projects are focussed on developing and delivering management packages to facilitate high and sustainable yields. A new initiative, CottTech (a joint venture between CSIRO, CRDC and CSD), is one example of new research approaches being taken to achieve these yield and efficiency goals.