Healthier cotton soils through high input cereal rotations

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The use of cereal rotations in cotton systems – some recent history

The majority of cotton growers now favour sowing a cereal or leguminous crop in rotation with cotton rather than back-to-back cotton. The most recent survey (2005/06 season) indicated that across the industry rotations were used by 82% of cotton growers (Doyle and Coleman, 2007). Wheat was the favoured rotation crop with over 70% of NSW cotton growers who used rotation crops growing either a 1:1 or 2:1 cotton:wheat rotation (Hickman *et al*., 1998; Cooper, 1999).

A more recent survey by CSD (Cotton Seed Distributors Ltd.) in 2007 targeted growers that were achieving 12 bales /ha cotton yields. They found that 87% of crops that achieved at least 12 bales /ha were planted into fallow fields, the majority of which had grown a cereal since the previous cotton crop. New varieties and improvements in irrigation management are recognised as key drivers of high cotton yields in recent seasons, however yield stagnation or decline in back-to-back cotton fields has also become more apparent. Crop rotation is critical in order for irrigators to achieve the productivity improvements on offer in cotton. The impact cereal rotations have on the soil provides an insight into *how* crop rotations build an inherently more productive cropping system.

Rotational benefits of wheat for cotton soils

Wheat rotation crops can improve overall soil quality conditions across the range of climates where cotton is grown. Compared with back-to-back cotton the beneficial effects of wheat on soil quality include; better soil structure with greater resilience to tillage, greater recycling of leached N, higher levels of readily decomposable soil organic matter and a lower incidence of black root rot (Hulugalle and Scott, 2008).

In a review of several long-term on-farm and on-station field experiments Hulugalle and Scott (2008) found that better soil structure resulted by growing wheat after cotton than by growing legumes. This is because the intensity of wet/dry cycles is greater with wheat than with legumes, particularly in soils with sodicity at depth. Earlier research by Hearn (1986) and Constable et al. (1992) resulted in similar conclusions. They found that soil structure, N cycling, and lint yield and fibre quality of cotton were better after wheat rotation crops than after sorghum or soybean, or with back-to-back cotton. These responses were associated with structural degradation of the subsoil, with wheat rotation crops improving structure the most. McGarry (1995) and Pillai and McGarry (1999) concluded that intense and frequent wet/dry cycles are required in cracking clays to increase soil porosity and improve structural stability.

The above results may also partly be related to better rainfall conservation (CSD Extension and Development Team and Hulugalle, 2006) as cotton-wheat rotations include a ~10 month fallow between wheat harvest and cotton planting. Back-to-back cotton, cotton-soybean or cotton-sorghum rotations have shorter fallow periods that only occur during winter when relatively less rainfall occurs. Longer fallow periods in cracking clay soils enable more rainfall to be stored under cotton-wheat than under back-to-back cotton or cotton-summer crop rotations.

Measurement of soil water after cotton planting reveals that rotations produce different environments for crop establishment. Shown in Figure 1 and Table 1, hot drying conditions at planting can quickly reduce available soil water. Where cotton is planted into standing wheat stubble, evaporation losses almost halved. As a consequence, 1 week after watering up, there is an extra 0.21 ML/ha in the top 40 cm of the profile compared to a continuous cotton system.

Figure 1. Impact of crop rotation on soil moisture, 1 week after cotton planting.

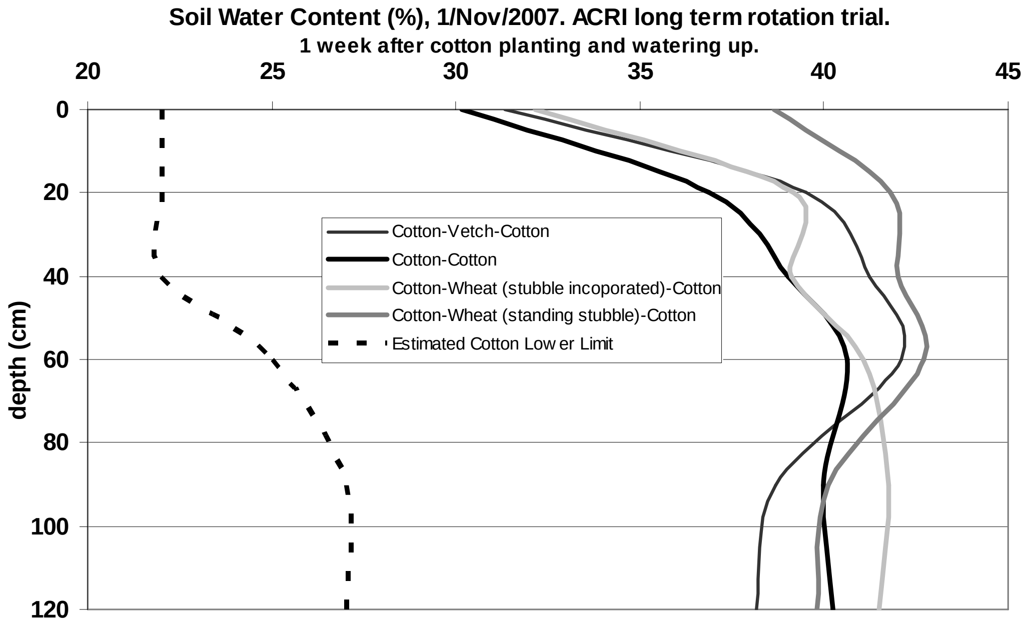


Table 1. Influence of crop rotation on stored soil moisture following cotton planting and watering up.

Rotation	Cotton-Vetch-Cotton	Cotton-Cotton	Cotton-Wheat (stubble incorporated)-Cotton	Cotton-Wheat (stubble standing)-Cotton	Value of standing wheat stubble over cotton-cotton
Plant Available Water mm 0-40 cm	64	55	62	76	0.21 ML/ha
Plant Available Water mm 0-120 cm	171	164	179	193	0.29 ML/ha

Why high input wheat?

While cotton in rotation with winter cereals is already common place, the majority of cereal crops currently grown are achieving low or inconsistent yields and are only in part delivering the rotational benefits and subsequent increases in profitability that are possible in the system.

Since the early 1980s little research has been done in Australia on irrigating wheat in cotton farming systems. This is mainly because through the late 1980s and 1990s water has been saved by growers for application to highly profitable cotton crops during the following summer. There is however some information available on the impact of fertilising wheat in cotton systems. This section presents some results from a trial in the Lower Namoi Valley where the wheat rotations were either fertilised on unfertilised.

Experiment Methodology

The experiment was established in 1993 on a commercial cotton farm near Wee Waa, north-western NSW on a self-mulching grey vertisol. The experimental treatments were: cotton followed by either “high” fertility wheat achieved through pre-plant application of urea (140 kg N/ha in 1993 and 120 kg N/ha in 1995 and 1997) or “low” fertility wheat where no nitrogenous fertiliser was used. Fertiliser was applied to cotton as anhydrous ammonia at a rate of 120 kg N/ha in 1994 and 1996, and 180 kg N/ha in 1998. All crops in the cropping sequences were irrigated by furrow irrigation. The wheat crops were watered up or pre-irrigated to enable establishment following cotton harvest. In-crop irrigations occurred only if rainfall was insufficient to meet crop needs. Timings of irrigations were determined by monitoring crops for visual signs of moisture stress. In 1993 there was no in-crop irrigation. In 1995 and in 1997 there was one in-crop irrigation.

Results

Wheat yield was increased by applying fertiliser, although the size of the increase varied each season. As shown in Table 2 yield increased by 27% in 1993, 19% in 1995 and 95% in 1997.

Table 2. Effect of fertility level on wheat grain yield. n.s., non-significant.

Season	High fertility wheat Grain yield t/ha	Low fertility wheat Grain yield t/ha	Mean Grain yield (t/ha)	Yield increase from high fertility
1993	5.2	4.1	4.6	27%
1995	3.1	2.6	2.8	19%
1997	4.5	2.3	3.4	95%
1999*	5.8	5.3	5.5	9%
Mean	4.7	3.6		

*1999, after the conclusion of the trial, uniform management across the field.

<u>AOV</u>

Variable	P <	$LSD_{0.05}$
Year	0.001	0.55
Cropping system	0.05	0.21
Year x Cropping system	n.s.	-

High fertility wheat did not significantly increase cotton lint yield and fibre quality but did return similar gross margins to the low input system from 1993 to 1997. The cumulative gross margin of the high fertility wheat system shows the extra cost of fertiliser was offset by the higher yields and protein percentages. Cumulative yields and gross margins are shown in Table 3. While there wasn't a strong profit advantage seen over the duration of this trial, the impact of the high fertility system on soil quality suggests greater potential productivity into the future. For example, the wheat crop sown in 1999, after the completion of the trial was grown using 145 kg N/ha applied prior to planting. In the areas where the high input treatments had been, yield was 9% higher than the areas where the low input treatments had been. Had water application been measured, we suspect that greater efficiency of use would also have been achieved in the high fertility treatment areas.

Table 3. Effect of N fertility in wheat rotations on cumulative cotton-wheat yields and gross margins. June 1993 to December 1997, ML = Mega litres of irrigation water.

Rotation crop	Cumulative cotton lint yield (b/ha)	Cumulative cotton seed yield (t/ha)	Cumulative wheat yield (t/ha)	Average wheat protein	Irrigation estimate (ML/ha)	Cumulative gross margin $AU/ha	$AU/ML
High N fertility wheat	16.4	5.5	12.9	12.2%	13.1	5845	410
Low N fertility wheat	17.1	5.6	9.0	10.3%	13.1	5590	401

The high fertility treatment resulted in the wheat increasing its root density, particularly at depths below 40 cm. The difference in rooting density between the treatments is shown in Figure 2. As a consequence of the increase in rooting density in the subsoil, the crop's capacity to extract soil water and nutrients was also increased.

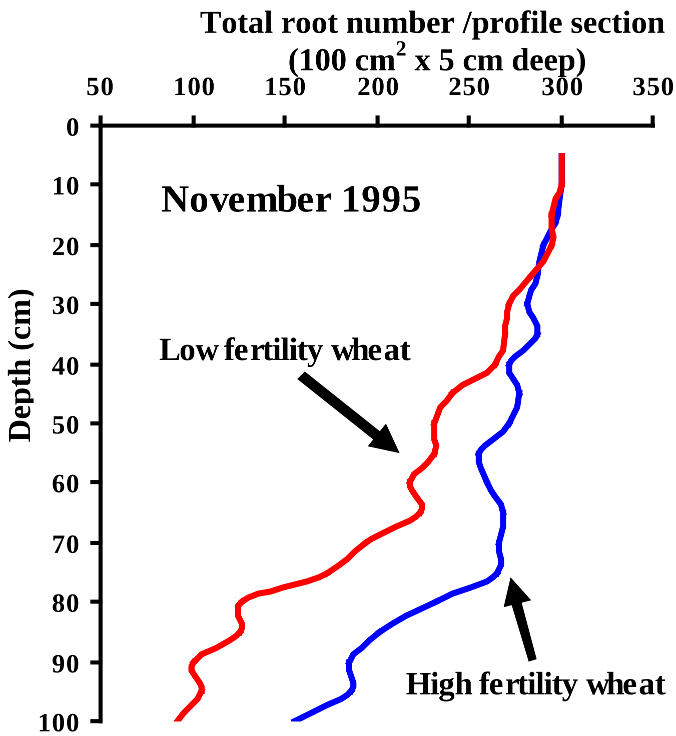
Figure 3 shows the pattern of water extraction through the soil profile for each treatment at four stages of crop development. The crop was irrigated in late August to compensate for below average rainfall. As the crops approach flowering in mid September, when daily water use is at its peak, the high fertility wheat has already drawn down more of the soil moisture held in the profile and so would require further irrigation to maintain the yield trajectory that was developed in the early half of the season. Higher yield is still achieved, but is limited by moisture stress through flowering and much of the grain filling period.

The higher yields achieved in the high fertility treatment were not just due to utilisation of the applied fertiliser. Over the 6 years of this trial, average N recovery from the subsoil (>0.6 m depth) by N-fertilised wheat was 110 kg N/ha per cotton-wheat cycle and by unfertilised wheat 76 kg N/ha (Hulugalle, 2005).

The presence of N in the subsoil has resulted from annual fertiliser applications to cotton. Assuming that today's cost of anhydrous ammonia is $AUS 1100/t, then the value of N recovered by the fertilised wheat was $AUS 121/ha/cycle and by unfertilised wheat $AUS 84/ha/cycle.

Not all of the recovered N is exported from the field in the wheat grain.

Figure 2. Effect of N fertility on wheat root density.

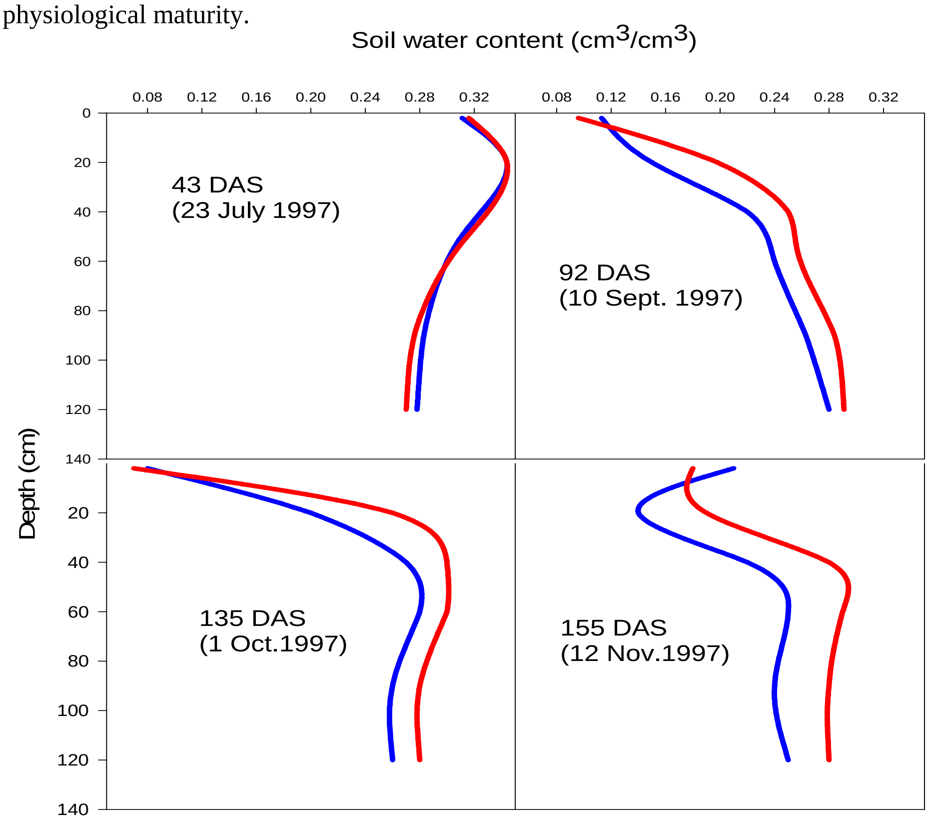


Some of the N is released into the topsoil by decomposing wheat stubble, steadily becoming available for use by the following cotton crop. Without wheat in the rotation, with sufficient root development for extraction from depth, this N would be leached from the system over time.

Figure 3. Effect of N fertility on soil water use by wheat crops at key growth stages.

Red lines: Low N fertility wheat Blue lines: High N fertility wheat

43 days after sowing (DAS) during tillering, 92 DAS prior to flowering, 135 DAS during mid grain fill and155 DAS at physiological maturity.



Other nutrients taken up in higher quantities by the fertilised wheat crop, relative to the low fertility treatment, are also released as the wheat stubble decomposes and can be taken up be the following cotton crop. This is shown in Table 4.

Table 4. Nutrient uptake by wheat (Nov. 1993) and the following cotton crop (Mar. 1995)

(N, S, P, Ca, Mg, K and Na are in kg ha^{-1}, and Zn, B, Mn and Cu are in g ha^{-1}). * , ** and *** denote that values differ significantly at the 95%, 99% and 99.9% levels of probability, respectively. ns = not significant.

Wheat stubble:

Treatment	N	S	P	Mg	Ca	K	Na	Zn	B	Mn	Cu
Fertilized wheat[1]	165	15	20	14	20	193	5	195	32	868	477
Unfertilized wheat	94	11	15	11	15	138	4	85	30	717	345
P <	*	ns	*	***	*	*	ns	ns	ns	ns	**

Wheat grain:

Treatment	N	S	P	Mg	Ca	K	Na[2]	Zn	B	Mn	Cu
Fertilized wheat[1]	102	8	19	7	2	19	117	96	10	32	55
Unfertilized wheat	79	6	15	5	1	15	82	77	10	23	100
P <	*	*	*	*	*	*	ns	**	ns	*	ns

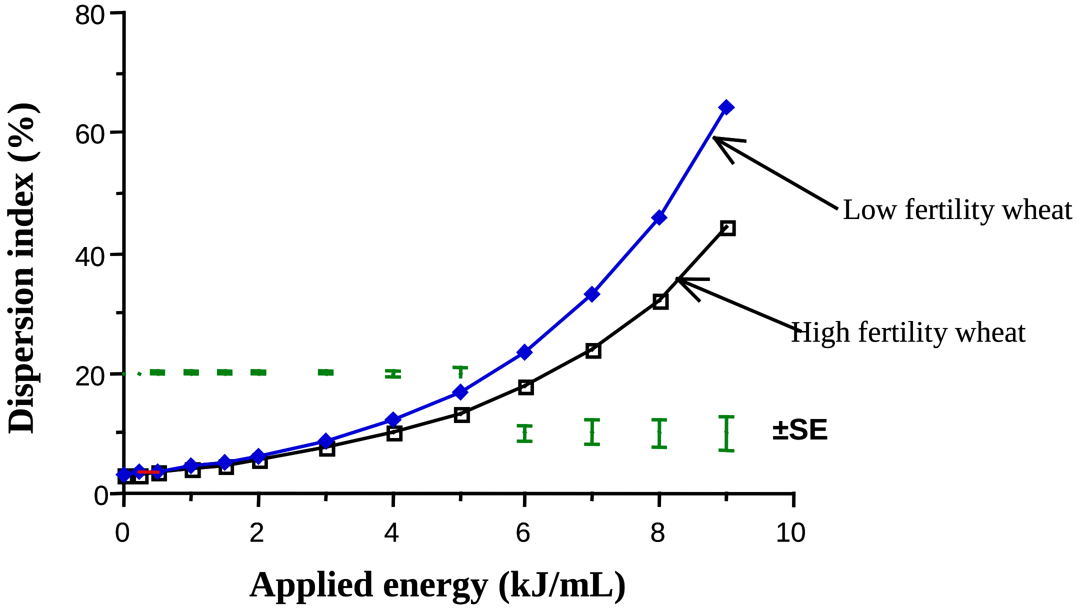
Cotton stubble:

Treatment	N	S	P	Mg	Ca	K	Na	Zn	B	Mn	Cu
Fertilized wheat[1]	145	30	12	28	153	89	8	70	331	241	35
Unfertilized wheat	108	21	9	22	127	61	6	48	298	213	22
P <	*	*	**	ns	ns	*	*	*	ns	ns	***

1. Fertilizer applied at a rate of 140 kg N ha^{-1} as urea.
2. Na in wheat grain is given in g ha^{-1}.

In addition, soil structural stability was also improved by high fertility wheat. Shown in Figure 4, soil in the high fertility system disperses less when energy is exerted upon it, such as in response to trafficking or tillage. This may be due to the more intense drying of the soil than low fertility wheat.

Figure 4. Effect of fertilising wheat on soil structural stability in the 0.15–0.30 m depth. A high value of dispersion index indicates low structural stability.



Fertilising wheat rotations crops had beneficial effects on soil quality. Over the medium to long term, the improvement achieved in soil quality creates a buffer in nutrient cycling and increases accessibility of moisture stored in the subsoil. The soil in which this trial was carried out was relatively fertile. Soil organic carbon in the surface 0.15 m averaged 1.3% whereas in most cotton soils it ranges between 0.7 and 1.0%. Given this inherent fertility, it is likely that more benefit would flow onto cotton where the system is adopted in less fertile soils. Optimal irrigation in combination with fertiliser use is likely to have further intensified the resulting soil and crop benefits.

Residual effects of wheat rotation crops

Weaver et al. (2004) observed that differences in deep drainage in a sodic grey clay reflected rotation history three years after individual rotation treatments had been discontinued. This was attributed to long-term changes in soil structure and exchangeable sodium percentage. Deep drainage out of the 0.9 m and 1.2 m depths were in the order of ex-cotton-wheat > ex-back-to-back cotton >> ex-cotton-dolichos. Leaching of excess soluble salts and exchangeable sodium were also in the same order (Weaver et al., 2004).

Three years after a cotton-wheat sequence was discontinued, studies by Hulugalle et al. (1997) showed that improvements in subsoil porosity, water extraction, aggregate stability and soil organic carbon, and reductions in sodicity were leading to higher cotton yields. The cotton-wheat sequence on permanent beds had been in place for a 10 year period. Changes made to the soil were detectible even after five years of back-to-back cotton.

Similarly in two on-farm experiments conducted in a medium and a heavy clay (both grey clays), the residual effects of wheat rotation crops were characterised by higher soil organic carbon and better structure up to five years after the rotation sequences had been discontinued (Hulugalle et al., 2006).

Biodiversity and soil quality

Ants are an indicator species for soil biological quality in cotton-based farming systems. They are strongly influenced by management practices such as; irrigation, cultivation and broad-spectrum insecticide use (Reid et al., 2003). Hulugalle et al. (1997) observed that ant and springtail numbers were higher where a cotton-wheat rotation was grown using permanent beds compared with back-to-back cotton using conventional tillage.

Ants are able to change soil quality in cotton fields, particularly in areas near and adjacent to ant hills and foraging paths. Ant activity increases soil organic matter, nitrates and phosphates; reduces sodicity; and improves soil structure and deep drainage (Hulugalle, 1995; N'Kem et al., 2000). N'Kem et al. (2000) also noted that pH of soil in foraging paths were lower than that of bulk soil. This difference may result in improving uptake of Ca, Mg, K and phosphates in foraging paths by increasing the solubility of their respective carbonates and sulphates. In a comparison of N-fertilised and unfertilised wheat rotation crops, N'kem et al. (2002) observed that numbers of ants and other insects were higher in the unfertilised wheat due to higher soil temperatures caused by less ground cover.

High soil microbial activity is frequently assumed to reflect better soil quality, although field-based studies are yet to conclusively demonstrate this in cotton-based farming systems in the literature. Similarly, less than a handful of studies have compared the effects of different cropping systems on soil microbial activity. Luelf et al. (2006) reported that in comparison with back-to-back cotton, cotton-vetch and cotton-wheat-vetch rotations, soil microbial biomass at 72 days after sowing was highest under a cotton-wheat rotation where wheat stubble had been incorporated into the beds (Luelf et al., 2006). It was however, difficult to ascertain whether this higher microbial biomass conferred any benefit to the soil or the crop. Bell et al. (2006) who examined the effects of several rotations under dryland conditions, concluded that microbial activity was related to the length of the fallow rather than to the rotation per se, and that it was restricted to the soil's surface layers. In addition to total microbial activity in soil, several studies have documented the physiology and agronomy of VAM (vesicular arbuscular mycorrhiza) in cotton crops and associated soil (Nehl et al., 1996, 1998, 1999). VAM activity is reported to confer many benefits with respect to soil fertility, carbon storage, structural and hydrological properties and crop nutrition. However, under conditions typical of Australian commercial cotton farming practices, there appears to be no differences among crop rotations with respect to VAM populations (Hulugalle et al., 1999b, 2004). These authors also noted that VAM numbers were above critical threshold values (25% of total root length) for cotton among all rotations studied.

Profitability

Analyses of the results from the CRDC–Cotton CRC funded rotation experiments conducted near Warren, Merah North and Narrabri indicate that average gross margins/ha were highest with back-to-back cotton. This was because there were more cotton crops grown compared to in cotton-rotation crop sequences. Importantly it was not because gross margins were higher per cotton crop.

Results from many cotton-rotation system experiments conducted in New South Wales and Queensland between 1993 and 2007 show that cotton yield/ha was lowest or equal lowest with back-to-back cotton, particularly if intensive tillage was practiced (Hulugalle and Scott, 2008). Poor cotton lint yields under back-to-back cotton mean that this system is at greater risk of financial losses in years when the cotton lint price is relatively low, costs increase significantly or seasonal conditions limit yield potential.

The cotton-wheat systems generally returned higher gross margins/ML of irrigation water than back-to-back cotton across the experiments (Hulugalle and Scott, 2008). On many cotton farms today, where irrigation water is currently more limited than land, cotton-wheat rotations are likely to be more profitable.

Similarly to cotton, high wheat yields can be chased with inputs but returns on investment may be low if other factors are limiting the response (Staaper, 2005). Paddock choice, variety choice and plant establishment are important factors identified in building a crop that is responsive to water and nitrogen to yield above 7-8 t/ha. There needs to be a stepwise approach to achieving yield improvements.

In Summary

There are significant benefits to both the grains and cotton industries from the development of a water use efficient, highly productive winter cereal crop option for irrigation. A cropping system in which there is a combination of winter and summer cropping will reduce overhead costs, spread risk, increase the farm's overall water use efficiency, reduce the likelihood of herbicide resistant weeds, increase the efficiency of storing soil moisture, assist in maintaining or even improving soil organic carbon and increase profitability. While cotton is likely to be more profitable on a $/ha basis, given the reductions in water licences, a cereal rotation using half the irrigation input of cotton with competitive $/ML profitability to cotton, will encourage substantial expansion of irrigated cereal area while allowing stable areas of cotton production.

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