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Pulse crops in rotation with cereals can be a profitable alternative to nitrogen fertiliser in central Queensland

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Abstract. Empirical and simulation results from three crop rotations incorporating cereals, pulses and nitrogen (N) fertiliser application were examined over 4 years in a subtropical environment, central Queensland, Australia. The hypothesis was that pulse crops in rotation with cereals would be a viable alternative to applying N fertilisers and would improve farm business economic performance provided the yield potential of pulses were not compromised by planting into very low soil water situations. Empirical data and simulations with the Agricultural Production Systems Simulator model were used to give insights into the N contribution, yield benefit to cereals and overall economic performance of the inclusion of pulses into the rotation. The field trial rotations included: rotation 1: sorghum and wheat in an opportunity crop rotation (called cereals-only), rotation 2; cereals grown following a fallow with a pulse crop immediately after (called cereal double-cropped pulse) and rotation 3, pulses grown following a fallow with a cereal crop immediately after (called pulse double-cropped cereal).

Empirical and simulated results indicated that the cereal double-cropped pulse rotation produced the highest average annual gross margins using prices at that time. In the simulations, when pulse crops were included in the rotation, no additional N fertiliser was required and the lowest chance of negative gross margins was obtained. The cereal double-cropped pulse rotation produced the largest trial and simulated gross margins. The pulse double-cropped cereal rotation produced greater gross margins than the N-deficient cereals-only rotation but significantly lower than the cereal double-cropped pulse rotation. Simulations indicated that the cereals-only rotation could be made profitable when the soil was 'topped-up' to 100 kg available N/ha before planting, or by 40 kg N/ha to each cereal crop. Chickpea and mungbean contributed an average of 35 and 29 kg N/ha, respectively, in the field trial.

A minimum of 100 mm of the stored soil water at planting was needed to reduce the risk of negative returns. By planting only when the soil contained adequate water, the cereal double-cropped pulse rotation may provide a valuable supplement to farm income while simultaneously reducing the need for N fertilisers on the cereals. Alternatively, in a rotation with cereals only, modest amounts of fertiliser N will maintain profitability with minimal levels of financial risk.

Additional keywords: APSIM, cereals, fertiliser, nitrogen, pulses, rotations.

Introduction

Almost all types of summer and winter crops can be grown in central Queensland (CQ). However, cropping is dominated by sorghum and wheat production (up to 200 000 ha each per annum) and previously, sunflowers (Spackman and Garside 1995). The area planted to chickpea is increasing and is expected to reach a record level of 60 000 to 70 000 ha in 2010 (www.dpi.qld.gov.au/30_17095.htm). Mungbean are more commonly grown in the slightly cooler region of the Dawson Callide. Because of the inherently variable rainfall and hence variable stored soil water conditions, the cropping system is highly opportunistic in an aim to obtain higher cropping frequency and returns than fixed cropping (Carrol *et al.* 1993). Growers will plant crops when stored soil water is adequate but also chose crops that meet essential needs of subsequent stubble cover, provide disease breaks and respond to market price fluctuations.

Continuous cropping has depleted soil nitrogen (N) (Garside *et al.* 1992). Additional N must be supplied to meet crop demand and maintain production in many areas of CQ (Dalal and Mayer 1990; Armstrong *et al.* 1999*b*), particularly where cereals dominate the rotation. Where N fertiliser is applied to cereals, growers take significant financial risk well ahead of crop returns. High fertiliser prices add to the financial loss where N fertiliser is applied to crops that fail because of low soil water supply or because of poor seasonal growing conditions.

Pulse crops can serve the dual purpose of potentially providing N for subsequent cereal crops as well as being an intrinsically financially viable crop (Spackman and Garside 1995). Pulse crops can supply or spare soil N (Doughton and Holford 1997) but the quantity supplied varies widely. Angus *et al.* (2001) collated 135 sites years of data and reported increases in wheat yield following pulses crops ranging from 8 to 131%. A mean yield increase of 40–50 was cited. The sites were mostly in southern Australia. Northern Australian data included Dalal *et al.* (1998) who reported a 39% wheat yield increase following chickpea. Armstrong *et al.* (1999*a*) reported a net N balance of –80 kg/ha for mungbean in CQ but an increase in subsequent grain yield of sorghum of greater than 100% that persisted into the second and

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third sorghum test crops. Grain protein was increased by up to 5%. Doughton and McKenzie (1984) reported increased in sorghum yields of 70% following green and black gram mungbean and equated this to an equivalent N fertiliser rate of 68 kg/ha. Doughton and Holford (1997) tabulated 21 results from pulse/cereal rotation experiments from Queensland and northern New South Wales (NSW). The benefits were presented in terms of fertiliser equivalents and percentage cereal yield increase. Fertiliser equivalents ranged from 35 to 100+ kg N/ha and yield increases of 3–104% (mean of 52%). Kirkegaard *et al.* (2004) proposed that fertiliser equivalents may overstate the N benefit from pulses because of non-nutrition related factors. Felton *et al.* (1998) reported a 54% increase in grain yield and a 5% increase in grain protein in wheat following chickpea compared with wheat following wheat (mean of 9 crop/years), some of which related to reduction in crown rot incidence. In northern regions, chickpea and mungbean are routinely used within 'fixed' rotations (making as a disease 'break') as well as double-cropped (opportunistic) situations, mainly in response to market prices as well as the 'other' factors that potentially accrue. Chickpea are ideally suited for incorporation into current reduced tillage and no-till systems (Herridge and Holland 1992) especially as an opportunity crop after cereals. Such conditions usually mean that biological N fixation is enhanced under the usually low soil N conditions in opportunistic rotations and most pulses emerge more successfully than cereals where seed is placed deep to seek sufficient moisture for germination. However, pulses are sometimes grown as a double-crop after cereals, when low soil water conditions increase the risk of crop failure. Whish *et al.* (2007) identified 100 mm of stored soil water as giving an 80% chance of a breakeven yield in western areas of Queensland. Dalal *et al.* (1998), Felton *et al.* (1998), Marcellos *et al.* (1998) and Doughton and Holford (1997) have all reported benefits of chickpeas in rotation in southern Queensland and northern NSW. However, there has been little quantification of their potential benefits of pulses in rotation in CQ. Growers in CQ (a semiarid, subtropical environment) have machinery, farm layouts and skills to manage the extremely variable environment. However, further intensification of cropping is an important goal on some farms to better manage reducing terms of trade, relatively high investment in capital equipment, and debt servicing needs (Spackman and Garside 1995).

Using empirical and simulation modelling methods, this study determined the N and water dynamics and the profitability of rotating pulses with cereals in CQ. Short- and long-term perspectives are considered regarding: the comparable returns from rotations involving pulses in rotation with cereals, the likely N contribution from pulses and what additional N fertiliser would be required for cereals to maximise profits if pulses are not included. Stochastic efficiency analysis principles were used to compare the rotation and N fertiliser scenarios (Hardaker *et al.* 1997, 2004).

Materials and methods

Field site

A field experiment was conducted over 4 years at Jambin, CQ (24°8′S, 150°20′E). The soil at the site was a Chromosol (Isbell 1996), known locally as Callide alluvial. The soil had a silty clay-loam surface, overlying black-brown clay. It had a sand, silt and clay content of 66, 15 and 19%, respectively. Other element concentrations in the top 10-cm layer were: bicarbonate P 46 mg/kg, organic C 1.05%, total N 0.091%, DTPA Zn 0.59 mg/kg, Cl 27 mg/kg, sulfate-sulfur 4 mg/kg, exchangeable K 0.77 mg/kg, exchangeable Na 0.47 meq%, exchangeable Ca 11 meq%, pH 7.2 (1 : 5 soil : water) .

Soil water characterisation

The upper soil water storage capacity was determined by the ponding method as described by Dalgliesh and Cawthray (1998). The crop lower limit was determined by sampling the dry profile over the wheat crop in the first season. The water-holding capacity was calculated by difference and used with subsequent simulations.

Treatments and statistical analysis

A randomised complete block field design with three replications of 18 treatments; comprising three cropping phases of rotations 1 and 3 (no N applied) and three cropping phases by four N rates (applied to cereal crops) for rotation 2. The three crop rotations are illustrated in Table 1. Crop data were analysed separately by ANOVA for each cropping season. A set of orthogonal contrasts compared the effects of previous N for effect of previous pulse crops and current N for cereal crops. Cropping phases were

Table 1. Schematic representation of crop rotations including phases which are used to start the rotations in different years in order to capture the effects of the different seasons

Thus, there were three phases within each rotation and three replicates of each phase each year

Season:		1995	1996		1997		1998	
Rotation	Phase	Winter	Summer	Winter	Summer	Winter	Summer	Winter
Rotation 1	1	Wheat[A]	Sorghum[A]	Fallow	Sorghum[A]	Wheat[A]	Fallow	Wheat[A]
Cereals-only	2	Wheat[A]	Fallow	Wheat[A]	Sorghum[A]	Fallow	Sorghum[A]	Wheat[A]
	3	Fallow	Sorghum[A]	Wheat[A]	Fallow	Wheat[A]	Sorghum[A]	Fallow
Rotation 2	1	Wheat[B]	Mungbean	Fallow	Sorghum[B]	Chickpea	Fallow	Wheat[B]
Cereal double-crop pulse	2	Chickpea	Fallow	Wheat[B]	Mungbean	Fallow	Sorghum[B]	Chickpea
	3	Fallow	Sorghum[B]	Chickpea	Fallow	Wheat[B]	Mungbean	Fallow
Rotation 3	1	Fallow	Mungbean	Wheat[A]	Fallow	Chickpea	Sorghum[A]	Fallow
Pulses double-crop cereal	2	Chickpea	Sorghum[A]	Fallow	Mungbean	Wheat[A]	Fallow	Chickpea
	3	Wheat[A]	Fallow	Chickpea	Sorghum[A]	Fallow	Mungbean	Wheat[A]

[A] Nil N applied to cereal crops (i.e. 1 plot/phase).

[B] N rates of 0, 50, 100, 150 kg N/ha applied to cereal crops (i.e. 4 plots/phase).

offset by 1 year to assess seasonal variation in comparisons of the three crop rotations. Thus, each phase of the three rotations was represented every year between 1995 and 1998. The Agricultural Production Systems Simulator (APSIM) validation was conducted using an *R*-squared test as well as root mean square of the error (RMSE) as a useful visual model validation indicator (Mayer and Butler 1993).

Crops were sown with a research plot-planter of 2-m width. Each plot consisted of two passes of the planter which for wheat, chickpea and mungbean resulted in 14 rows spaced 0.25 m apart, and 6 rows of sorghum spaced 0.65 m apart. Plots were 15 m long.

Chickpea (cv. Amethyst) and wheat (cv. Hartog) were planted each winter season. In summer, mungbean (cv. Emerald) and the sorghum cultivars, MR Buster in 1995–96 and 1996–97 and Thunder in 1997–98 were planted. Planting rates were 55 kg/ha for wheat. Plant densities were 7.5 plants/m^2 for sorghum plots, 30 plants/m^2 for mungbean and 20 plants/m^2 for chickpea. The pulses were inoculated with appropriate rhizobium bacteria in slurry using methyl cellulose as a sticker.

Zero-till cultivation practices were used with fallow spraying with Glyphosphate and appropriate herbicides for in-crop weed and insecticides for insect control.

Fertiliser application

Urea was applied at planting in bands 0.5 m apart at the centre of every alternate inter-row space at a depth of 7 cm. This single band supplied the two adjacent crop rows. Alongside the outside crop row, a tine supplied the appropriate quantity of fertiliser for a single crop row. A cone distributor on the plot-planter was used to uniformly apply a weighed quantity of fertiliser. N as urea was applied at rates of 0, 50, 100 and 150 kg N/ha only to cereals in rotations 2**.** All crops received an equivalent of 10 kg P/ha as the phosphate-based fertiliser Granulock Starter Z (21.9% P, 2.5% Zn, 9.4% N, 2.2% S; Incitec Pivot Ltd, Southbank, Victoria, Australia), applied with the seed at sowing through the attached fertiliser box.

Crop measurement and chemical analysis

Biomass production was measured from samples of one row of 1-m length at flowering. Samples were dried for 24 h at 65°C and weighed. At maturity, the inner 10 of 14 rows of wheat, or the inner four rows of sorghum, were harvested from each plot. For pulse crops all rows were harvested. The plot length was 15 m.

Grain N percentage was determined from a Kjeldahl digest, and results expressed as grain protein percentage using appropriate N-protein conversion factors, and were corrected for grain moisture to 11% for wheat, 13.5% for sorghum, and 12% for mungbean and chickpea.

Soil sampling and analysis

Prior to each planting, two soil cores, each 48 mm in diameter, were taken to a depth of 1.5 m from each plot. The cores were divided into increments of: 0–10, 10–30, 30–60, 60–90, 90–120 and 120–150 cm. The two cores were combined for each depth increment and mixed, from which two separate subsamples were taken. From one subsample, wet soil weights were taken in-field. These samples were subsequently dried at 105°C for 2 days in a forced draught oven, and then re-weighed. The other subsample was dried at 40°C and ground to <2 mm for colourimetric determination of nitrate using 10 g of soil extracted in 100 mL of 2 mol KCl/L (Best 1976).

Soil sampling and analysis for N contribution of pulses

The N contribution of the pulse rotation was calculated by comparing total soil mineral N after fallows following the pulse and cereal crops (Table 2). Sampling occurred immediately before winter crops in 1996, 1997 and 1998 following a summer fallow after either a wheat or chickpea crop the previous year. Similarly, the contribution from mungbean was calculated from sampling before the summer crop in 1996–97 and 1997–98 following a winter fallow after either sorghum or mungbean.

Rainfall and irrigation

The rainfall was extremely variable often with extended periods of less than the long-term monthly average quantity (Fig. 1). To ensure survival of some crops, supplementary irrigation (50 mm) was applied at the times indicated.

Crop simulation modelling

Four simulation studies were conducted using version 5.1 APSIM (Keating *et al*. 2003). The model was used to simulate:

(1) A validation study against the trial results using the soil water and nitrate values, planting dates and N fertiliser rates for each crop were set as per the field trial. Rainfall was collected on-site and the quantity of irrigation was added to the rainfall files at the appropriate dates. The total soil water-holding capacity had previously been determined on-site.

(2) Long-term analysis of the same crop rotations as the field trial using a rule-based method to better mimic real-world scenarios (Table 3). Climate data encompassing 1900–2006 from a nearby meteorological station (Wowan Post Office 039102) were used.

Table 2. Subset of starting soil water and soil NO_3 measurements

Note: the difference between a and a_1, b and b_1, etc. was used to calculate nitrogen contribution of the pulses. Maximum water-holding capacity 170 mm

Sampling time	Soil water (mm)	Soil NO_3 (kg/ha)
Pre-winter crop 1996, fallowed from wheat	135	63 * a
Pre-winter crop 1996, fallowed from chickpea	118	114 * a_1
Pre-summer crop 1996–97, fallowed from sorghum	172	93 * b
Pre-summer crop 1996–97, fallowed from mungbean	179	135 * b_1
Pre-winter crop 1997, fallowed from wheat	167	91 * c
Pre-winter crop 1997, fallowed from chickpea	137	107 * c_1
Pre-summer crop 1997–98, fallowed from sorghum	156	55 * d
Pre-summer crop 1997–98, fallowed from mungbean	130	70 * d_1
Pre-winter crop 1998, fallowed from wheat	149	73 * e
Pre-winter crop 1998, fallowed from chickpea	170	110 * e_1

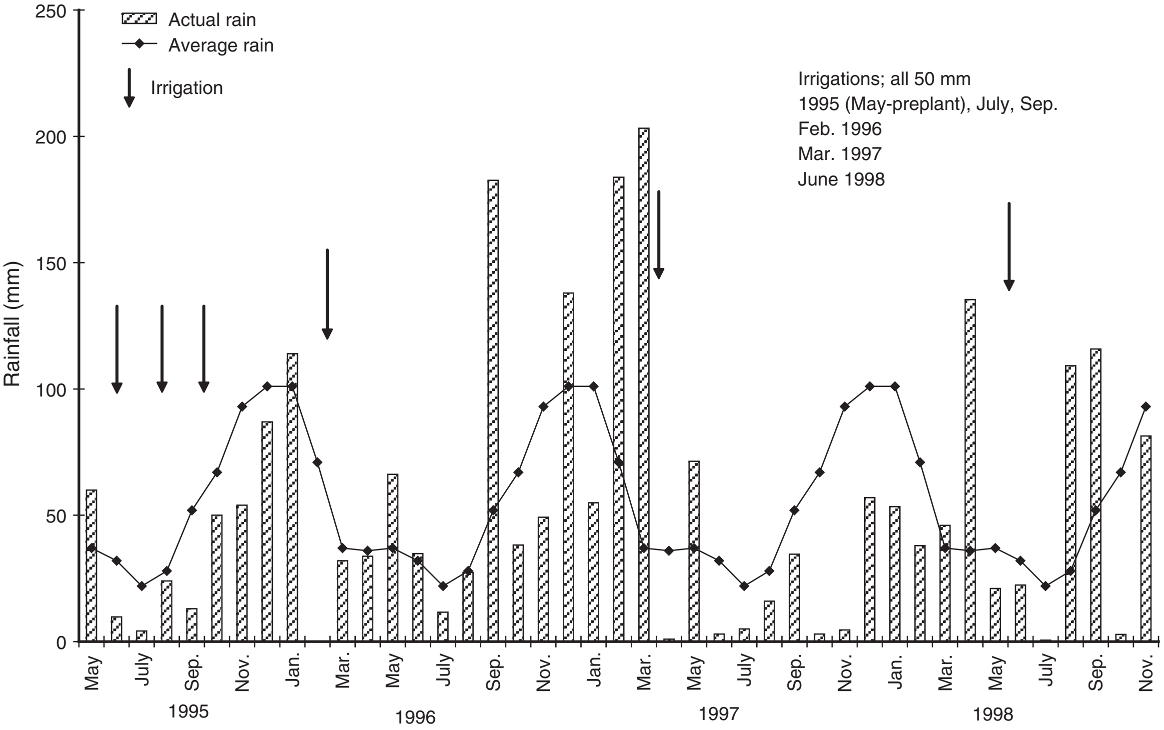

Fig. 1. Mean and actual rainfall at the trial site. Irrigation, all 50 mm, were applied May 1995 (before planting), July and September 1995, February 1996, March 1997 and June 1998.

Table 3. Set-up factors for long-term APSIM crop rotation simulations

	Wheat	Chickpea	Sorghum	Mungbean
Planting date range	15 Apr. to 15 June	30 Apr. to 15 June	1 Oct. to 15 Feb.	1 Oct. to 15 Feb.
Rainfall trigger (mm/days)	15/10	15/10	15/10	15/10
Surface soil wetness (fraction of extractable soil water)	0.6–0.8	0.6–0.8	0.6–0.8	0.6–0.8
Cultivar	Hartog	Amethyst	Buster	Emerald
Plant population (plant/m^2)	75	30	7	30
Planting depth (mm)	50	50	50	50
Row spacing (mm)	350	500	1000	500

(3) The effect of seven levels of soil water threshold triggers for planting of the pulses within a cereal double-crop pulse rotation. No fertiliser was added for the cereals and the soil water 'trigger' for the cereals within the rotation was assumed to be 85 mm (50% of capacity).

(4) Outcomes of eight N fertiliser strategies on the cereal-only rotation, including set rates and tactical N applications. The topping-up strategy involved increasing the soil N level at planting to the prescribed soil N quantities.

Economic analysis

The modelled yields were converted to distributions of gross margins using grain prices and variable costs for each crop shown in Table 4.

Table 4. Prices and costs used for the gross margin analyses as at time of field trial (1995–98)

	Price ($/t)	Variable costs ($/ha)^A
Sorghum	180	278
Wheat	150	169
Mungbean	400	209
Chickpea	350	259

^{A}Excludes N fertiliser. N fertiliser price was $1.00/kg elemental N.

Scenarios were compared using a trade-off between risk (chance of negative gross margins) and mean annual gross margin and also a method of stochastic dominance analysis known as stochastic efficiency with respect to a function (Hardaker *et al.* 2004). This method orders a set of risky alternatives in terms of certainty equivalents for a specified range of attitudes to risk. In this analysis, a relative risk aversion coefficient range (r_rW) of 0.5–4 was used (Anderson and Dillon 1992). Absolute risk aversion cumulative density functions for all scenarios were produced using a 'wealth' term estimated to be $200/ha. The absolute risk aversion coefficient (ARAC) was created from values of r_rW/wealth.

Stochastic dominance analysis was undertaken using Simetar (Richardson *et al.* 2006).

Results

Part 1. Field trial

Contribution of pulse crops to the N balance

Growing chickpea and mungbean increased the N supply to the soil by 35 and 29 kg/ha, respectively (Table 5).

The contribution varied widely in direct proportion to the harvest index (Fig. 2). The contribution was measured after 7-month fallows following chickpea, before wheat in 1996 and 1998, mungbean before sorghum in 1997–98 and mungbean before wheat in 1996. The N contribution potentially consists of N spared, N fixed and any change to soil mineralisation caused by the inclusion of the pulse crop.

Effect of pulse crops on grain yield and protein of subsequent cereal crops

Grain protein of wheat was increased by a prior chickpea crop in 1996 and 1998, and in sorghum by prior chickpea crops in 1995–96, 1996–97 and 1997–98 (Table 6). Grain protein of wheat was increased by a prior mungbean crops in 1997 and 1998 and in sorghum in 1996–97 and 1997–98.

Grain yield of wheat was increased by a prior mungbean crop (double-cropped) in 1998 compared with wheat double-cropped from sorghum. However, there was also increased stored soil water (56 mm) after mungbean, compared with that after sorghum (34 mm) (data not shown). Similarly, the grain yield of sorghum was increased by a prior chickpea crop (double-crop) in 1996–97 compared with a wheat crop. However, in 1997–98, the reverse occurred. Low stubble levels after the chickpea were noted and the silty soil had the appearance of surface-sealing. However, there was only 9 mm less soil water following chickpea so the reason for the difference is unclear.

Table 5. Contribution to soil NO_3 supply from previous pulse crop. Soil NO_3 measurements were taken at the end of the fallow between the two crops listed

	Cropping season			
Rotation	1996	1997	1998	
	kg N/ha			
Chickpea-wheat[A]	114	107	110	–
Wheat-wheat[A]	63	91	73	Mean
Difference	51	16	37	35
	Cropping season			
Rotation	1996–97	1997–98	–	–
	kg N/ha			–
Mungbean-sorghum[A]	135	70	–	–
Sorghum-sorghum[A]	93	55	–	Mean
Difference	42	15	–	29

[A] 7-month fallow nil N applied.

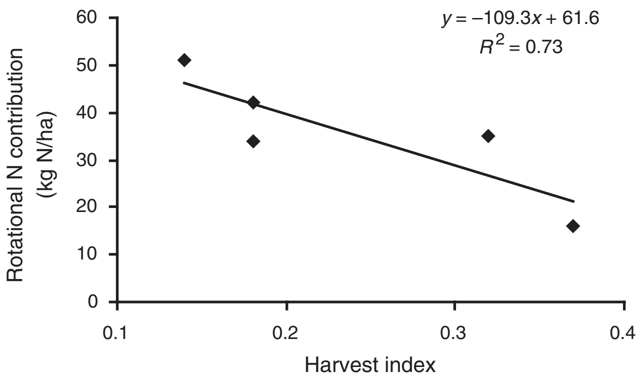

Fig. 2. The contribution of nitrogen from a previous pulse crop as a function of harvest index (field experiment).

The value of fertiliser N on cereals

When no N fertiliser was applied, the resultant grain proteins of cereals crops in the *cereals-only* rotation were very low: 9.9% in wheat in 1995 and 7.5% and 8.4 in sorghum in 1995–96, 1996–97, respectively (Table 6). The addition of N fertiliser significantly increased grain protein levels of wheat in 1995 by up to 4.8%, but not in the sorghum rotation in 1995–96. In the latter case, the in-crop rainfall was in the lowest 10% of recorded quantities.

In rotations in which a pulse crop preceded a cereal crop, application of 50 kg/ha N fertiliser further increased grain protein in three out of four cases. Higher N rates provided no additional increase. As mentioned previously, the prior pulse crops alone had already increased grain protein concentrations by up to 2%.

Effect of stored soil water on crop yields (double-cropped compared with longer fallows)

The very short period of fallow intrinsic in double-cropping usually resulted in a very low quantity of soil water at planting compared to those following longer periods of fallow (Table 7). Consequently, yields with double-cropping were, in three cases, significantly less than the corresponding yield with fallowing. This reflects the riskiness of planting in such situations. However, as occurred in 1997, double-cropping does not necessarily involve a planting with limited soil water. Because of high rainfall after harvest of the previous crop, the quantity of stored soil water available after the short fallow was the same as that after the longer fallow (170 mm, 100% full profile).

Gross margins (field trial and simulation modelling)

The cereal double-crop pulse rotation produced the highest gross margins in the field and simulated (Table 8). The cereals-only rotation produced moderate gross margins in the field because the soil fertility of the trial site was initially high and cereal crops did not experience N deficiency until late in the trial period. The gross margins from the pulse double-crop cereal rotation were more dependent on the pulse yields which were high for chickpea in 1997 but much lower in 1998. Mungbean yields were consistently low.

Table 6. Effect of rotation and N fertiliser rates on grain yields (t/ha), grain protein (%) within the crop rotations
* $P < 0.05$; **$P < 0.01$; *** $P < 0.001$; n.s., $P > 0.10$. N, nitrogen rate

Season	1995		1996		1997		1998	
Sow-harvest date (dd/m)	30/5–20/10		16/5–17/10		22/5–27/10		19/6–17/10	
Rotation/fertiliser								
Wheat–wheat	Yield	Protein	Yield	Protein	Yield	Protein	Yield	Protein
Wheat grain yields (t/ha) and protein (%)								
0N	3.19	9.9	2.49	12.4	2.3	13.2	2.91	12.7
Chickpea–**wheat**								
0N	–	–	2.5	13.6	2.46	13	3.59	13.0a
50N	–	–	2.66	14	2.71	13.7	3.91	13.5b
100N	–	–	2.84	14.2	2.63	13.9	3.99	13.8b
150N	–	–	2.68	14	2.68	13.9	4.08	13.8b
			n.s.	($P < 0.06$)	n.s.	n.s.	n.s.	***
Sorghum–**wheat** (3-month fallow) 0N	–	–	1.05	12.4	1.38	12.3	0.28	11.7
Mungbean–**wheat** (3-month fallow) 0N	–	–	1.65	12.5	1.94	14	1.8	12.7
			n.s.	n.s.	n.s.	*	***	***

Chickpea grain yields (t/ha)

Season	1995	1996	1997	1998
Sow-harvest date (dd/m)	30/5–20/10	20/6–17/10	6/6–27/10	19/6–4/11
Rotation/fertiliser				
	Yield			
Wheat–**chickpea** (7-month fallow)	0.85	1.17a	2.23a	1.42
Sorghum–**chickpea** (3-month fallow)	–	0.29b	2.53b	1.29
		***	***	n.s.

Sorghum grain yields (t/ha) and protein (%)

Season	1995–96		1996–97		1997–98	
Sow-harvest date (dd/m)	16/1–9/5		12/11–25/2		3/2–1/6	
Rotation/fertiliser						
Wheat–**sorghum** (14-month fallow)	Yield	Protein	Yield	Protein	Yield	Protein
0N	3.91	11.8	–	–	–	–
50N	3.97	12.4	–	–	–	–
100N	4.01	11.8	–	–	–	–
150N	3.93	12.0	–	–	–	–
	n.s.	n.s.				
Mungbean–**sorghum**						
0N	–	–	3.6	10.1	3.33	10.6
50N	–	–	3.84	11.9	3.25	11.6
100N	–	–	4.06	12.0	4.32	11.4
150N	–	–	3.82	11.8	2.91	11.8
Sorghum–**sorghum** 0N	–	–	3.46	7.8	3.77	8.4
			n.s.	**	($P < 0.067$)	*
Wheat–**sorghum** (3-month fallow) 0N	4.39	10.3	1.77	7.5	3.26	10.3
Chickpea–**sorghum** (3-month fallow) 0N	5.13	11.8	2.90	9.2	1.88	12.1
	n.s.	($P < 0.07$)	($P < 0.06$)	**	**	**

Mungbean grain yields (t/ha)

Season	1995–96	1996–97	1997–98
Sow-harvest date (dd/m)	16/1–3/4	12/11–24/1	3/2–1/6
Rotation/fertiliser			
		Yield	
Wheat–**mungbean** (3-month fallow)	1.25	0.74	0.54a
Sorghum–**mungbean** (7-month fallow) 10P	–	0.88	0.78b
	n.s.	n.s.	***

Table 7. The effect of low levels of soil water at planting with double-cropping (usually with negligible or very short fallow; 3 months at most) compared with crops planted after a 7-month fallow

Crop	Season	Double-cropped plots[A]		Fallowed plots	
		Soil water at planting (mm)[B]	Crop yield (t/ha)	Soil water at planting (mm)[B]	Crop yield (t/ha)
Wheat	1996	92	1.1	134	2.7
Chickpea	1996	32–43	0.3	117	1.2
Chickpea	1997	170 (full profile)	2.53	170 (full profile)	2.23
Chickpea	1998	44–68	1.3	170	1.4

[A] The range of soil water is the result of differing N rates on the previous crop: the higher the N rate on the previous cereal, the lower the subsequent stored water.

[B] Total soil water-holding capacity was 170 mm.

Table 8. Comparison of mean gross margins from the trial and modelling outcomes

	Mean gross margin ($/ha)[A]				
	Trial 1996 and 1996–97	Trial 1997 and 1997–98	Long-term modelled		
		Cereal-only + 0N		Cereal-only + 40 kg N/ha	Cereal-only + top to 100 kg N/ha
Cereals-only	165	193	69	**262**	**280**
		Cereal + pulse crops			
Cereal double-cropped pulse	**291**	**240**	**337**	–[B]	–
Pulse double-cropped cereal	236	145	248	–	–

[A] The gross margin is the average of all winter and summer crops in the relevant rotations during the period 1996–98. The 1995–96 results were not included because of differing fallows before the first crop.

[B] Modelled N rates were applied to 'cereal-only' rotation.

See Fig. 6 for results of the full range of modelled tactical fertiliser N strategies.

Part 2. Modelled outcomes – validation APSIM simulation of the wheat, sorghum, mungbean and chickpea crops using inputs from the field trial

The relationship between actual trial and simulated yields for wheat was very close (Fig. 3). Sorghum yields were less accurately predicted by simulation, the range of predicted and observed yields were 3.5–5.0 and 3.0–4.5 t/ha, respectively; over-prediction occurring most commonly. Similarly, pulse yields were less accurately predicted by simulation; both mungbean and chickpea were over-predicted for most seasons. The overall RMSE was 623.1 kg/ha while the $R^2 = 0.69$.

Part 3. APSIM long-term cropping analysis – economic analysis

Simulation modelling was further used to evaluate the economic benefits (gross margins) of these rotations over a longer term than for the 4 years of the field trial or the simulated 4-year trial. When crop rotations are simulated over 99 years of climate records for the location of the trial, the wider range of weather experienced provided a better comparative evaluation of these rotations. The cereal double-crop pulse rotation produced a significantly higher gross margin ($337/ha) than other rotations (Table 8 and Fig. 4).

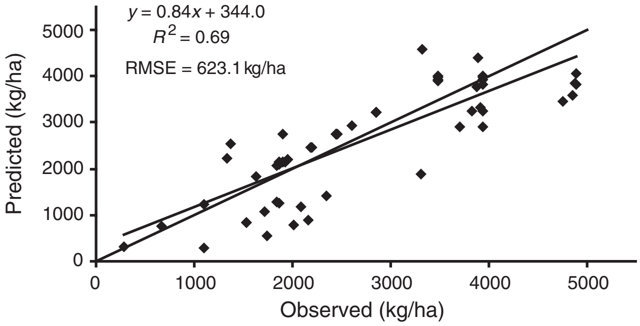

Fig. 3. Observed *v.* predicted yields for wheat, sorghum, mungbean and chickpea, resetting soil water and nitrogen to the values measured in the field trial and using actual rainfall and irrigation data.

The cereals-only rotation with nil N fertiliser, produced the lowest long-term gross margin ($69/ha average with negative gross margins in 39% of years) because of the severe N deficiency (Fig. 4). The pulse double-crop cereal rotation produced an intermediate gross margin ($248/ha). Alternative strategies based on a modest annual amount of N fertiliser (40 kg/ha) or topping-up the total soil N supply to 100 kg N/ha or more, increased gross margins but not to the level achieved with the cereal double-crop pulse rotation.

The stochastic efficiency analysis indicate that the cereal double-cropped pulse and the pulse double-cropped cereal rotations are the most desirable depending on the growers' attitude to risk (Fig. 5). For growers with lower levels of risk aversion (ARAC < 0.012), the cereal double-cropped pulse rotation would have been the preferred option. This represents the majority of the farming population ranging from those that are 'rather risk-averse' ($r_rW = 2.0$) through to 'hardly risk-averse at all' ($r_rW = 0.5$) (Hardaker 2000). Very risk-averse growers may prefer the pulse double-cropped cereal rotation, in this case trading off potential higher returns for less downside risk than the cereal double-crop pulse rotation.

The fertiliser strategies for the cereal-only rotations would be a less-preferred option to those including the pulse crops. However, the 100N top-up strategy would be preferred over the 40N set rate

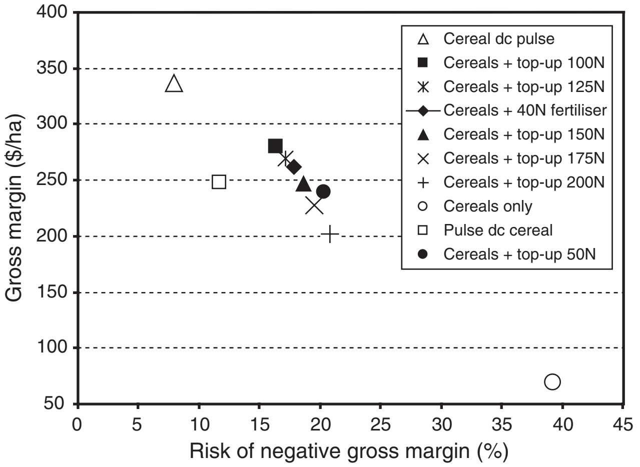

Fig. 4. Modelled long-term gross margins as a function of risk (per cent of crops with negative gross margins). The results are from the field trial (open symbols) and the modelled tactical nitrogen fertiliser strategies (other symbols).

strategy by the majority of growers except those that were extremely risk-averse (Fig. 5).

Modelling tactical N fertiliser decisions

Several tactical N strategies were modelled and the gross margins and risks of negative returns were compared with the cereal-pulse rotations (with nil N) (Fig. 4). The tactical N strategies involved topping-up the soil N content to the values 50, 100, 125, 175, 200 kg N/ha. Topping-up to 100 kg N/ha produced the highest gross margin with the least risk. Topping-up to 50 kg N/ha restricted yields in better seasons, while topping-up to greater than 100 kg N/ha increased costs, reduced gross margins and slightly increased the risk of negative returns. Conversely, the cereals-only rotation with nil N (rotation 1) produced a low long-term gross margin ($69/ha) with a very high (39%) chance of negative returns as would be expected when a system becomes severely N depleted. However, the 40 kg N/ha fixed-N rate and the tactical N rates increased gross margins and reduced risk compared with the nil-N treatment.

As previously described, the cereal double-crop pulse rotation (rotation 2 nil N applied) produced the highest gross margin ($337) and also had the lowest risk of negative returns (8%) of all strategies tested.

The effect of soil water at planting

In the field trial, three of the four double-crops that were planted on less than 100 mm of stored soil water resulted in yields (0.3–1.3 t/ha) that were substantially below the yield of crops double-cropped on a full profile of soil water (2.5 t/ha) or following a fallow period where more than 100 mm of soil water had accumulated (1.2–2.7 t/ha) (Table 7).

Simulation demonstrated that double-cropping with a minimum soil water at planting of 100 mm or higher reduced the number of low yielding pulse crops (<1 t/ha) and increased the mean annual gross margin for the cereal double-cropped pulse rotation (Fig. 6).

Discussion

N and water benefits of including pulse crops in rotation with cereals

The average N contribution of the pulse crops to the cropping system (35 kg N/ha) was the same as that reported by Dalal *et al.* (1998) and Weston *et al.* (2002) for the Warra experiment in southern Queensland and similar to that (33 kg N/ha) reported by Marcellos *et al.* (1998). Lucy *et al.* (2005) reported results from more than a decade (60 site.years) of chickpea-wheat rotation experiments in the northern grain regions. In NSW, there was on average, an additional 35 kg nitrate-N/ha in the 1.2-m profile after chickpea than in the continuous wheat. The increased soil nitrate following a pulse was attributed to both mineralisation of the N-rich residues and nitrate sparing by the legume, undoubtedly similar to this study. An often-quoted factor that may contribute to increased yields of subsequent cereal crops is increased water availability after the pulse. In this study the reverse was generally true and no consistent trend was found by Marcellos *et al.* (1998). The same could be said of the small increase (8 mm) in the data from Warra (Dalal *et al.* 1998; Weston *et al.* 2002). Felton *et al.* (1998) suggested that part of the yield increase in cereals following a pulse could be due to reduced crown rot incidence. A high N contribution from pulses cannot always be expected; when pulse yields are high relative to the vegetative biomass production, much of the fixed N is removed in grain (Doughton and Holford 1997). However, in CQ the frequency of

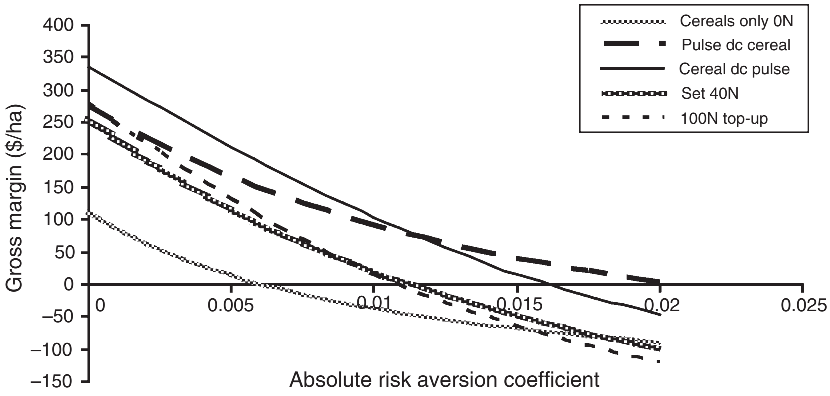

Fig. 5. Stochastic efficiency with respect to a function of crop rotation and nitrogen application scenarios assuming a negative exponential utility function.

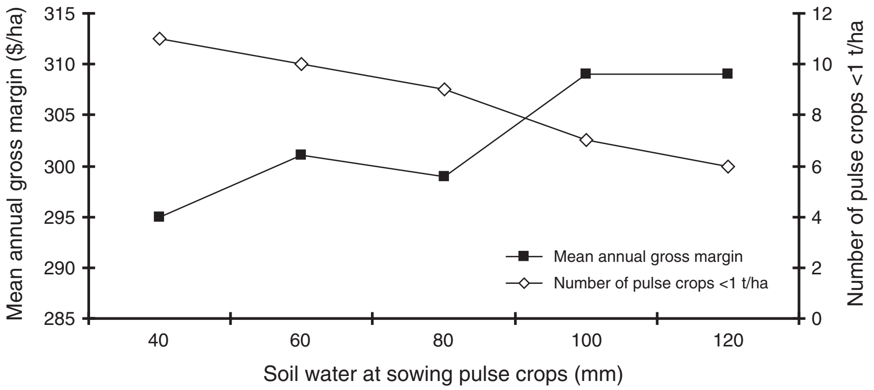

Fig. 6. The modelled effect of soil water at planting of pulse crops in a cereal double-crop pulse rotation on mean annual gross margin (■) and number of low-yielding pulse crops (<1 t/ha) (◇).

terminal stress is higher than in southern regions (Chapman *et al.* 2000) and hence a lower ratio of grain yield to vegetative biomass harvest index could often occur. While this disadvantages potential financial returns from the pulse crop, extra N benefit may accrue in a subsequent cereal.

Fertiliser N requirements for cereals in CQ

Both the field trial and simulation results demonstrated that only a modest quantity of N fertiliser was required to maximise the crop responses in wheat or sorghum. In the field trial, the most economic response to applied N occurred at the 50 kg N/ha rate. Simulation demonstrated that an annual rate of 40 kg N/ha or topping-up total N supply to 100 kg N/ha were equally effective economic strategies to supplement N supply. In order to establish the appropriate N rate, growers should measure or estimate stored soil water and N supplies before planting. Alternatively, applying 40 kg N/ha might be considered a low risk strategy for supplementing cereal N supplies in most rotations except following fallows of long duration.

The field trial demonstrated that under uncommon conditions of double-cropping in CQ when a moderate to high level of stored soil water (>100 mm) is available but soil N reserves remain low supplementary N fertiliser could increase grain protein and yield of cereal crops. Under more common low available soil water supplies (<100 mm) usually encountered in CQ with double-cropping, supplementary N fertiliser application in addition to N supply after pulse crop would usually be unnecessary.

Where sorghum was double-cropped following an unfertilised cereal crop, grain protein were below the critical level of 9.5% (Garside *et al.* 1992), confirming the impact of continuous cereal cropping on soil N in CQ cropping systems.

The field trial and simulated data (using rainfall received as well as available soil water and N as measured in the trial) have both highlighted the potential economic benefit from a cereal double-crop pulse rotation. In the field trial, the cereal crops that were grown after the pulse crops responded with increases in grain protein of up to 2%. In several instances yield grain yield was increased, the frequency of which would probably have been higher had the region not experienced a long period of drought.

Economic analysis

Incorporating pulses into a cereal-based system has potential economic benefits compared to a cereal-only system. The more commonly utilised rotation of cereal double-cropped pulse is shown to be the most potentially valuable rotation compared to all other rotations. However, the pulse double-cropped cereal rotation should not be disregarded except if agronomic factors such as a potential weed problem add to the riskiness of the rotation due to the fact that the main income is derived from the pulse.

A practical N application strategy could include topping-up the soil profile to 100 kg N/ha at planting when required although in the absence of knowledge of the soil N levels, applying 40 kg N at every planting event results in only a small penalty in the long term compared with the top-up to 100 kg N/ha or 125 kg N/ha strategies.

The effects of stored soil water on yields with double-cropping

In the CQ environment where rainfall is highly variable, grain growers are conscious of the need to plant a crop when the opportunity arises (Spackman and Garside 1995). One way to minimise the production risk associated with variable rainfall is to allow sufficient soil water accumulate before planting the pulse crop (Hayman *et al.* 2002; Moeller *et al.* 2009). The dilemma for CQ grain growers is that the duration that may be needed to increase soil water reserves adequately to reduce production risk will, over the long term, reduce frequency/intensity of cropping. Stored soil water can account for as much as 40% of yield variability in cropping systems of northern Australia (Dalal *et al.* 1997).

Simulating rotations over the long term (99 years) indicated that soil water supply at planting below 100 mm resulted in a large number of low yielding crops (<1 t/ha); while with 100 mm or more soil water at planting crop yields and gross margins were consistently greater. The 100 mm of minimum soil water at planting corresponds well with commercial advisor experience (G. Spackman, pers. comm., and M. Castor, pers. comm.). This field trial and simulation confirms that cereals or pulses planted on less than 100 mm of water (60% of the soils water-holding capacity) are at risk of achieving low yields and returns.

Supplies of soil water at sowing below 100 mm may result in increased cropping frequency/intensity over the long term. Such a low supply of soil water at planting however increases the risk of crop failure. Supplies of soil water at planting above 100 mm will reduce cropping frequency/intensity while enabling higher crop yields for the current crop and reduced risk of crop failure. Simulation modelling in this study has examined and quantified this trade-off. While it is understood that few growers will have access to such modelling outcomes, it is proposed that the minimum soil water of ~100 mm is a reasonable rule-of-thumb (supported by Whish *et al*. 2007). Hardaker *et al*. (1997) propose that information gathering and analysis is one way to manage risk. A commercially available decision-support package WhopperCropper (www.nutrientms.com.au/) provides capacity for advisors to demonstrate the yield and gross margin effects of different quantities of stored soil water across many regions (Nelson *et al*. 2002). Thus, there are compelling reasons for growers/advisors to measure stored soil water before double-cropping and plant only when sufficient water is stored (say ~100 mm as indicated in this study). This may increase the reliability of yield of pulse crops that are double-cropped after cereals. Other technologies have facilitated the introduction of chickpeas into cereal rotations without the need for rainfall for planting. Because of their large seed size, chickpeas can be planted at an optimum time through a dry surface soil. Chapman *et al*. (2004) have shown that cropping frequency could potentially be increased by an average of 96% across four sites in central Queensland if moisture-seeking planting strategies were used. However, it would be advisable to measure total soil water in order to minimise risk as previously described.

Other effects of pulses when in CQ rotations with cereal crops

Including pulse crops in rotations with cereal crops can provide more favourable positioning of N in the soil profile (McCown *et al*. 1988; Armstrong *et al*. 1999*a*). In this trial, N from a previous pulse crop was positioned deeper in the soil (data not shown) enabling its utilisation by the foraging roots of a following cereal crop. The improved availability of soil N after a pulse contrasts with the availability of fertiliser N applied to cereals after planting in seasons of negligible or light rainfall events. This outcome was observed in the field trial where fertiliser N applied to cereals was stranded in the dry surface soil and remained temporarily unutilised by the cereal.

One disadvantage of pulse crops in CQ crop rotations is the relatively small quantity of stubble produced and the rapidity with which this stubble decomposes. This can increase the risk of soil erosion in areas subject to high-intensity rainfall (Doughton and Holford 1997). In this trial there was an instance of surface sealing of the soil that was most likely attributable to inadequate surface cover.

In higher yielding environments, the total N requirement of cereals may exceed the ability of pulses to supply N (Marcellos *et al*. 1998). In the CQ environment, the usually modest cereal yields appear to be adequately supplied by the contribution of soil N remaining after the pulse crop. However, in southern Queensland and northern NSW, supplementary N fertiliser applications may be required on cereals following pulse crops because of the higher cereal yield potential. In any region, the requirement or otherwise for a supplementary N requirement can be confirmed by soil analysis (water and N) and budgeting techniques commonly used within the region.

Conclusion

Results of a 4-year field trial and a long-term simulation exercise indicated that growing an opportunity pulse crop after cereals can be a valuable strategy to supplement N supply in CQ cropping systems. The practice is particularly successful when the soil profile has been recharged with water (>100 mm) at the time of planting pulses or cereals.

Without the use of N fertilisers, continuous cropping of cereal crops will remain unprofitable and exacerbate soil N fertility decline. Simulation results indicate that over the long term, including a pulse in the rotation may supply sufficient N to the subsequent cereal to maintain economic returns. However, because of the relatively small (and variable) N contribution from pulses, soil fertility decline is likely to continue, albeit at a slower rate, than with continuous cereal cropping. Simulation results indicate that growers who wish to continuously crop cereals should consider fertiliser strategies that involve a top-up of the total soil N supply to 100 kg N/ha or alternatively apply 40 kg N/ha to each cereal crop.

Simulation modelling indicated that growing pulses on fallowed paddocks (with double-cropped cereals) may also be a satisfactory strategy if pulse prices remained relatively high and agronomic issues were very well controlled. The model outcome assumes no losses from weed or disease infestation which is a real risk with pulse crops. Thus, the disease risk, pest risk and price volatility of pulses may still dissuade farmers from utilising fallowed paddocks for pulses when the (usually) high quantity of stored soil water and N can be utilised for reliable returns from less risky cereal crops.

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