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Fertiliser N and P applications on two Vertosols in north-eastern Australia. 1. Comparative grain yield responses for two different cultivation ages

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Abstract. Nitrogen (N) and phosphorus (P) are the 2 most limiting nutrients for grain production within the northern grains region of Australia. The response to fertiliser N and P inputs is influenced partly by the age of cultivation for cropping, following a land use change from native pasture. There are few studies that have assessed the effects of both N and P fertiliser inputs on grain yield and soil fertility in the long term on soils with contrasting ages of cultivation with fertility levels that are running down *v.* those already at the new equilibrium. Two long-term N × P experiments were established in the northern grains region: one in 1985 on an old (>40 years) cultivation soil on the Darling Downs, Qld; the second in 1996 on relatively new (10 years) cultivation on the north-west plains of NSW. Both experiments consisted of fertiliser N rates from nil to 120 kg N/ha.crop in factorial combination with fertiliser P from nil to 20 kg P/ha.crop. Opportunity cropping is practiced at both sites, with winter and summer cereals and legumes sown.

On the old cultivation soil, fertiliser N responses were large and consistent for short-fallow crops, while long fallowing reduced the size and frequency of N response. Short-fallow sorghum in particular has responded up to the highest rate of fertiliser N (120 kg N/ha.crop). Average yield increase with fertiliser N compared with nil for 5 short-fallow sorghum crops was 1440, 2650, and 3010 kg/ha for the 40, 80, and 120 kg N/ha, respectively. Average agronomic efficiency of N for these crops was 36, 33, and 25 kg grain/kg fertiliser N applied. This contrasts with relatively new cultivation soil, where fertiliser N response was generally limited to the first 30 kg N/ha applied during periods of high cropping intensity.

Response to P input was consistent for crop species, VAM sensitivity, and starting soil test P level. At both the old and new cultivation sites, generally all winter cereals responded to a 10 kg P/ha application, and more than half of long-fallow sorghum crops from both sites had increased grain yield with P application. At the old cultivation site, average yield gain for 10 kg P/ha.crop treatment was 480 kg/ha for all winter cereal sowings, and 180 kg/ha for long-fallow sorghum. Short-fallow sorghum did not show yield response to P treatment.

Additional keywords: agronomic efficiency, sorghum, wheat, barley, chickpea, mungbean.

Introduction

The northern grains region is a subtropical cereal belt in eastern Australia, which extends from the Liverpool Plains region of New South Wales (~32°S) to the Central Highlands of Queensland (~22°S). It includes the agro-ecological zones of QLD Central, NSW North West/QLD South West, and NSW North East/QLD South East (Williams *et al*. 2002) and constitutes around 21% of the Australian grain area (National Land and Water Resources Audit 2002). The major cropping soils are black, grey, and brown Vertosols, black, red, or brown Sodosols, red and brown Chromosols, and Ferrosols (Webb *et al*. 1997). Sorghum and wheat are the dominant summer and winter grain crops, respectively (ABARE 2007), while globally, wheat, barley, and sorghum are the second, fourth, and fifth highest tonnage cereal crops (Food and Agriculture Organisation of the United Nations 2005).

Dalal and Mayer (1986*a*) report for 6 dominant soil types in southern Queensland, generally decreasing winter cereal yields with increasing periods of cultivation, following land use change from native vegetation or pasture. As cultivation age lengthened, losses of soil total and organic carbon (C) (Dalal and Mayer 1986*b*) and total nitrogen (N) (Dalal and Mayer 1986*c*) were described. Organic C generally declines because the amount of organic material returned to the soil decreases sharply. Loss of organic matter on cultivation is also accompanied by the release of its constituent nutrients such as N, P, and S (Dalal and Probert 1997; Dalal and Chan 2001). Similar results have been reported worldwide (Davidson and Ackerman 1993; McLauchlan 2006). Besides the net loss of nutrients associated with organic matter decline, available nutrient depletion can occur by one or more additional depletion processes such as nutrient removal in

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product and plant residue, soil erosion, burning, leaching, and denitrification of N (Dalal and Probert 1997). The National Land and Water Resources Audit (2001) reports high levels of nutrient export from the major areas of the northern grains region. Roy *et al*. (2003) suggest that without adequate restoration of soil fertility, the intensification of agriculture and continuous cropping may threaten its sustainability. After >30 years of cultivation, economic crop yields are not possible on some Darling Downs (southern Queensland) soils without the addition of N (Dalal and Mayer 1986*c*). In response to this decline in fertility, growers apply N and P fertilisers to optimise grain production, but areas with younger cultivation ages, which are running down, may have different nutrient requirements from areas that have reached equilibrium at a lower nutrient status. N and P are the nutrients most limiting crop production in the northern grains region (Dalal and Probert 1997), and N in particular comprises a significant variable cost component. During the early 1980s, many grain growers in the northern grains region expressed concern over multiple-site, single-year fertiliser experiments claiming that they were always positioned in the best place for that season. One grower suggested research be conducted on the one site for multiple years; a situation that they face, farming the same ground year-in, year-out. In response, several long-term, static-site, multiple-year fertiliser experiments were established in the northern grains region.

These experiments were initiated originally to establish the robustness over time of nutrient response relationships demonstrated in single-year experiments, and to establish the cumulative effect and efficacy of long-term N and P fertiliser application for grain production and soil fertility in cereal rotations. Having been operating for >10 years, the sustainability of long-term N and P fertiliser inputs can also be investigated. This study reports on grain yield responses of winter and summer crops to N and P fertilisers at 2 sites with contrasting cultivation age. Nutrient and carbon balances, and evaluation of the economic implications of N and P fertiliser applications will be reported separately.

Materials and methods

Experimental sites

The experimental sites are on the properties 'Colonsay' (27°28′S, 151°23′W) in the Formartin district of the Darling Downs, southern Queensland, and 'Myling' (28°54′S, 150°06′W) in the Tulloona district of the north-west plains of New South Wales.

Colonsay is a haplic, self-mulching, endohypersodic, black Vertosol (Isbell 1996*a*) of the Norillee Series (Beckmann and Thompson 1960; Vandersee 1975). Cultivation for farming commenced in the early 1940s (S. McWilliam, pers. comm.) and has rundown the soil's native fertility (Dalal and Mayer 1986*a*). Selected soil characteristics are shown in Table 1; reported results are from composite site sampling. Chemical methods at both sites refer to those described in Rayment and Higginson (1992). Sand, silt, and clay contents in the surface 0–0.1 m are 31%, 12%, and 57%, respectively. Mean soil test P concentration, determined using Colwell's sodium bicarbonate extraction method (hereafter termed Colwell P), as per Rayment and Higginson (1992), across the experimental area in 1985 was 10 mg/kg (0–0.1 m). Bulk density measures were estimated from analogue sites in Dalgliesh and Foale (1998).

Table 1. Soil characteristics (0–1.2 m) at Colonsay, Darling Downs, Qld

Depth (m):	0–0.1	0.1–0.3	0.3–0.6	0.6–0.9	0.9–1.2	Method
pH ($CaCl_2$)	7.7	8.1	8.1	8.3	8.4	4A2
EC (dS/m)	3.5	3.5	3.7	5.7	7.3	14B1
OC (%)^A	1.2	0.9	n.r.	n.r.	n.r.	6A1
Exch. cations (cmol (+)/kg)						
Ca	36	36	29	26	26	15D3
Mg	25	25	29	30	30	15D3
K	1.4	1.4	1.1	1.4	1.6	15D3
Na	4.3	4.3	8.7	13	16	15D3
Bulk density (g/cm^3)	1.01	1.06	1.05	1.05	1.09	

n.r., Not recorded. ^{A}1994 site data.

The Myling experiment is in an area recently changed from grazing to cropping. The site was cleared of open forest in 1987 (J. Gooderham, pers. comm.), with cereal grain production commencing in 1996. Soil characteristics are shown in Table 2. The soil is a haplic, self-mulching, endohypersodic, black Vertosol (Isbell 1996*b*). Sand, silt, and clay contents in the surface 0–0.1 m are 47%, 3%, and 50%, respectively. Colwell P (0–0.1 m) across the experimental area in 1996 was 19 mg/kg. Bulk density measures were estimated from nearby analogue sites in Dalgliesh and Foale (1998), and Daniells *et al*. (2002).

Experimental designs and histories

Colonsay

Experimentation commenced in 1985 at Colonsay where 2 experiments were operating concurrently, a nitrogen (N) × phosphorus (P) fertiliser rate, and a sulfur (S) fertiliser rate experiment. The experiment had 3 replicates in blocks. Main-plot treatments were 4 N rates at each of 4 P fertiliser rates (Table 3). The split-plot component had altered since the

Table 2. Soil characteristics (0–1.2 m) at Myling, Tulloona, NSW

Depth (m):	0–0.1	0.1–0.3	0.3–0.6	0.6–0.9	0.9–1.2	Method
pH ($CaCl_2$)	7.1	7.9	8.1	7.9	7.9	4A2
EC (dS/m)	0.9	1.6	2.5	6.4	12.0	14B1
OC (%)^A	0.96	0.83	n.r.	n.r.	n.r.	6A1
Exch. cations (cmol (+)/kg)						
Ca	35	38	30	32	31	15D3
Mg	11	12	12	13	12	15D3
K	1.4	1.8	1.1	1.1	1.2	15D3
Na	1.8	4.6	11	11	11	15D3
Bulk density (g/cm^3)	1.06	1.07	1.08	1.10	1.14	

n.r., Not recorded. ^{A}1996 site data.

Table 3. Experimental designs at Colonsay, Darling Downs, Qld, from 1985 to 2004

Years	Main plots N rate (kg/ha.crop)	Main plots P rate (kg/ha.crop)	Split plot	Plot area
1985–89	0, 40, 80, 120	0, 10, 15, 20	Zn, plus & minus	2 by 25 m long, 5.0 m wide
1990–95	0, 40, 80, 120	0, 10, 15, 20	N, base & +40 kg	50 m long, 2.5 m wide
1996–98	0, 40, 80, 120	0, 10, 15, 20	N, pre-plant *v.* at-sowing	50 m long, 2.5 m wide
1999–	0, 40, 80, 120	0, 5 (was 15), 10, 20	N, pre-plant *v.* at-sowing	50 m long, 2.5 m wide

experiment commenced (Table 3), to keep abreast of changing fertiliser and cropping management, and widen the scope of the investigations. Results of the S rate experiment will be reported separately.

From 1985 to 1989, fertiliser treatments were a pre-plant band applied with crops then sown by the site co-operator. From 1990 onwards, a small plot research planter was used for both fertiliser and seed applications. Sowing rates and row spacing were those used for commercial crops. N fertiliser was applied as urea (46% N) and P as triple superphosphate (20.7% P), which was banded in the seed furrow.

Myling

At Myling, main-plot treatments were 5 N rates at each of 3 P rates with 3 replicates in blocks (Table 4). Nitrogen was pre-plant applied in a split-plot design as urea (46% N) or anhydrous ammonia (82% N). Triple superphosphate (20.7% P) was banded in the seed furrow.

Table 4. Experimental designs at Myling, Tulloona, NSW, from 1995 to 2004

Years	Main plots N rate (kg/ha.crop)	Main plots P rate (kg/ha.crop)	Split plot	Plot area
1995–	0, 30, 60, 90, 120	0, 10, 20	N, anhydrous ammonia *v.* urea	20 m long, 2.5 m wide

Crop agronomy

Colonsay

From 1985 to 2004, 19 crops were sown: 11 grain sorghum (*Sorghum bicolor*), 4 barley (*Hordeum vulgare*), 3 wheat (*Triticum aestivum*), and 1 chickpea (*Cicer arietinum*) (Table 5). In 1991–92, 60 kg N/ha as anhydrous ammonia was applied across the entire site during routine fertiliser application of the surrounding area. Analysis of that year's grain yield investigated residual N effects on top of the 60 kg N applied. The chickpea crop in 2000 and the sorghum sown in 2004 were not harvested due to drought. Wet conditions during autumn 2003 prevented any pre-plant application, so N was applied at sowing to all treatments. Annual rainfall varied from 282 mm in 2000 to 930 mm in 1988. Mean annual rainfall at the site was 555 mm (1985–2005), which was lower than the long-term mean of 616 mm at nearby Mount Irving (Clewett *et al*. 2003). Growing-season rainfalls measured at the site taken as Nov.–Mar. for summer crops, and June–Nov. for winter crops were generally within range of historic values covering rainfall amounts from 90% of years (230 mm Nov.–Mar., 95 mm June–Nov.) to 50% (median) rainfall values (360 mm Nov.–Mar., 187 mm June–Nov.) (Clewett *et al*. 2003).

Table 5. Crop agronomy at Colonsay, Darling Downs, Qld, from 1985 to 2004

Crop season	Crop	Fallow rainfall (mm)	Pre-plant N	Sowing date	Variety	In-crop rainfall (mm)	Harvest date
1985	Barley		21.iv.85	–	–	217[A]	16.xi.85
1986–87	Sorghum	503[A]	8.viii.86	–	–	205[A]	10.iii.87
1987–88	Sorghum	383[A]	–	–	–	358[A]	iii.88
1988–89	Sorghum	538[A]	–	2.x.88	–	164[A]	–
1989–90	Sorghum	326[A]	24.viii.89	27.xi.89	Goldrush II	251[A]	–
1990	Barley	180[A]	6.vii.90	6.vii.90	Grimmett	88[A]	–
1991–92	Sorghum	392[A]	60 kg across site	16.xii.91	MR51	201	10.iv.92
1992	Barley	86	All AS	18.vi.92	Grimmett	44	11/12.xi.92
1993	Barley	175[A]	–	27.*v*.93	Tallon	133[A]	–
1994–95	Sorghum	420[A]	–	–	–	176[A]	–
1996	Wheat	1037[A]	10.iii.96	20.vi.96	Cunningham	131	20.xi.96
1997–98	Sorghum	413	12.viii.97	17.x.97	MR Buster	389	12.iii.98
1998–99	Sorghum	448	20.x.98	6.x.98	Magnum MR	193	13/14.iii.99
1999–2000	Sorghum	201	6.viii.99	5.xi.99	Magnum MR	370	30/31.iii.00
2000	Chickpea	85	n.a.	24.vi.00	Amethyst		Failed crop
2001–02	Sorghum	343	20.iv.01	24.x.01	MR43	346	6.iii.02
2002	Wheat	58	n.a.	28.vi.02	Hybrid Mercury	73	13.xi.02
2003	Wheat	545		13.vi.03	Strzlecki	152	15.xi.03
2004	Sorghum	912	22.iv.04	24.xii.04	Bonus MR		Failed crop

–, Not recorded; n.a., not applicable. [A]Estimate from daily rainfall records and likely agronomic operations in relation to rainfall events.

Weed control using standard herbicide control measures was adequate in most years other than for the 1999–2000 sorghum crop when an inter-plot application (using a shielded spray unit) of 1.6 L/ha of Roundup CT® (450 g/L glyphosate; Monsanto Australia Ltd) on 24 December 1999 was necessary. Off-target damage from spray drift was visually assessed on 18 January 2000 and a damage score was applied as a co-variate during statistical analysis to adjust grain yield.

Myling

At Myling from 1996 to 2004, 9 crops were sown: wheat (*Triticum aestivum* and *Triticum turgidum*) 4 times, grain sorghum twice, and barley, chickpea, and mungbean (*Vigna radiata*) once each (Table 6). Prior to sowing wheat in 1996, the site was sown to forage sorghum in 1994 and grazed. Sowing rates and row spacings for all crops were those used for commercial crops. Annual rainfall varied from 453 mm in 2003 to 840 mm in 2004. Mean rainfall at the site was 558 mm. Long-term mean rainfall at Boggabilla was 610 mm (Clewett *et al*. 2003). Growing-season rainfalls at the site were generally within range of values from 90% of years (202 mm Nov.–Mar., 134 mm June–Nov.) to 50% (median) rainfall values (318 mm Nov.–Mar., 239 mm June–Nov.) (Clewett *et al*. 2003).

The centre 2 rows (of 4) were harvested for the mungbean crop of 2000–01 following floodwater submerging the site in February 2001. One replicate was lost and population reduced in the outside rows.

In the barley crop in 2001, grass weeds were controlled using 400 g/L tralkoxydim (a herbicide of the cyclo-hexanediones group); however, due to differential stages of crop phenology resulting from fertiliser treatments, some growth stages suffered damage. Damage was visually assessed and a damage score applied as a co-variate during statistical analysis to adjust grain yield.

Grain harvest and plant analysis

Grain was mechanically harvested and grain yields (kg/ha) were calculated on a harvested area basis with adjustment to the maximum moisture level accepted for grain receival: 12.0% moisture for mungbean, 12.5% for wheat and barley, 13.5% for sorghum, and 14% for chickpea.

Agronomic efficiency of nitrogen

Novoa and Loomis (1981) and Ladha *et al*. (2005) defined agronomic efficiency of N [AE_N] as the ratio of yield to N supply, and in this study it is applied as:

$$AE_N = (Y_F - Y_0)/F_N = \Delta Y/\Delta N \text{ in kg/kg}$$

where Y_F is grain yield (kg/ha) in treatment with fertiliser N applied per plot (F_N, kg/ha) and Y_0 is crop yield (kg/ha) measured in control treatment with nil fertiliser N application.

Statistical analysis

ANOVA, co-variate statistics, and mean separation using least significant differences (l.s.d.) at the 5% level were calculated using GenStat 9th Edition (Payne *et al*. 2006). Reported mean grain responses and statistical effects are the main plot effects for all N rates, and nil, 10, and 20 kg P rates.

Results

General overview of significant fertiliser effects on grain yield at both sites

Combining both sites, either N or P fertiliser treatments significantly influenced grain yield in 24 out of 26 crops harvested (Tables 7, 8). The 2 crops not influenced by either N or P were both sorghum at Colonsay grown on long fallow (>9 months). Responses to N and P treatments at both Colonsay and Myling are independent effects, with significant interactions of any magnitude between N and P rarely recorded. Only 3 site years indicated significant interaction between N and P, all at Colonsay (Table 7). In one short-fallow sorghum crop (1987–88), +P treatments increased grain yield as N rate increased; however, P itself was not significant. The 2 remaining significant N × P interactions were winter cereals double-cropped into sorghum (1992 and 2002), where again as N supply increased, +P treatments increased yield, although the site mean yield was low (<1000 kg/ha). P was a highly significant effect in both years.

Nitrogen fertiliser effects on grain yield

At Colonsay, N fertiliser responses were significant in 13 of 17 harvested crops (Table 7). Generally, all crops grown on short

Table 6. Crop agronomy at Myling, Tulloona, NSW, from 1996 to 2004

Crop season	Crop	Fallow rainfall (mm)	Pre-plant N	Sowing date	Variety	In-crop rainfall (mm)	Harvest date
1996	Wheat	n.r.	11.iii.96	20.*v*.96	Pelsart	235	12.xi.96
1997–98	Sorghum	490	19.viii.97	20.x.97	MR, Buster	269	24.ii.98
1998–99	Sorghum	594	6.x.98	12.x.98	MR, Buster	234	15.iii.99
1999	Wheat, durum	132	19.*v*.99	18.vi.99	Yallaroi	181	11.xi.99
2000	Wheat	400	4.iv.00	1.vi.00	Sunvale	107	7.xi.00
2000–01	Mungbean	319	4.xii.00	24.i.01	Emerald	201	4.iv.01
2001	Barley	38	18.*v*.01	31.*v*.01	Dash	151	4.xi.01
2003	Chickpea	712[A]	24.x.02	26.*v*.03	Howzat	154	27.x.03
2004	Wheat	545	2.iv.04	10.vi.04	Hybrid Mercury	143	9.xi.04

n.r., Not recorded. [A]Estimate from daily rainfall records on-site and Rainman yearly total at Boggabilla for 2002.

Table 7. Significant effects of N and P fertiliser treatments on grain yield at Colonsay, Darling Downs, Qld, from 1985 to 2003
*$P<0.05$; **$P<0.01$; ***$P<0.001$; n.s., not significant

Crop season	Fallow length	Crop	Significant effects N	P	N × P
1985	Long	Barley	***	n.s.	n.s.
1986–87	Long	Sorghum	***	***	n.s.
1987–88	Short	Sorghum	***	n.s.	**
1988–89	Short	Sorghum	***	n.s.	n.s.
1989–90	Short	Sorghum	***	n.s.	n.s.
1990	Double	Barley	***	***	n.s.
1991–92	Long	Sorghum	n.s.	n.s.	n.s.
1992	Double	Barley	***	***	***
1993	Short	Barley	n.s.	**	n.s.
1994–95	Long	Sorghum	n.s.	n.s.	n.s.
1996	Long	Wheat	***	***	n.s.
1997–98	Long	Sorghum	n.s.	**	n.s.
1998–99	Short	Sorghum	***	n.s.	n.s.
1999–2000	Short	Sorghum	***	n.s.	n.s.
2001–02	Long	Sorghum	**	*	n.s.
2002	Double	Wheat	***	***	***
2003	Short	Wheat	***	***	n.s.

Table 8. Significant effects of N and P fertiliser treatments on grain yield at Myling, Tulloona, NSW, from 1996 to 2004
*$P<0.05$; **$P<0.01$; ***$P<0.001$; n.s., not significant

Crop season	Fallow length	Crop	Significant effects N	P	N × P
1996	Long	Wheat	***	n.s.	n.s.
1997–98	Long	Sorghum	*	***	n.s.
1998–99	Short	Sorghum	***	n.s.	n.s.
1999	Double	Wheat	***	*	n.s.
2000	Short	Wheat	***	***	n.s.
2000–01	Double	Mungbean	n.s.	*	n.s.
2001	Double	Barley	**	n.s.	n.s.
2003	Long	Chickpea	n.s.	*	n.s.
2004	Short	Wheat	n.s.	***	n.s.

fallow or double-cropped were N responsive, irrespective of being a winter or summer cereal (Fig. 1), with only one crop (barley in 1993, Fig. 1*i*) not responding. N fertiliser effect on long-fallow crops was generally smaller or not responsive.

At Myling, N fertiliser significantly influenced grain yield in 6 of 9 harvested crops (Table 8). During a high-intensity cropping period from 1996 to 2001, when 7 crops were sown, both winter and summer crop grain yields showed varied responses (Fig. 2). Only 3 crops recorded large positive increases to N treatment, one short fallow into sorghum and the others double-crop winter cereals. In all cases, 30 kg fertiliser N delivered the largest yield response.

Winter crop grain yield responses to N

At Colonsay, winter cereals were sown following long fallow twice, short fallow twice, and double-cropped into sorghum stubble 3 times. The 2 long-fallow crops, barley in 1985 (Fig. 1*a*) and wheat in 1996 (Fig. 1*k*), each had an N response. In 1985 the first 40 kg N applied increased yield by 1000 kg/ha, a 34% increase. A small yield increase of 240 kg/ha occurred with a further 40 kg N/ha. A 1340 kg/ha yield increase occurred in 1996 with the first 40 kg N/ha applied (31%), with a further 400 kg/ha gained from the next 40 kg N/ha. The average yield increase for long-fallow winter cereal with 40 kg fertiliser N/ha was 1170 kg/ha. Two short-fallow winter cereals were sown, barley in 1993 (Fig. 1*i*) and wheat in 2003 (Fig. 1*q*). N treatment did not affect yield in 1993. In 2003, N response was highly significant, with a linear grain yield increase of 1700 kg/ha up to the 80 kg N/ha rate, 75% greater than the control. Three double-cropped winter cereal crops showed highly significant responses, barley in 1990 (Fig. 1*f*) and 1992 (Fig. 1*i*), and wheat in 2002 (Fig. 1*p*). The 1990 barley crop yield was 2590 kg under the 80 kg N/ha treatment (162% increase). In the lower in-crop rainfall years of 1992 and 2002, 40 kg N/ha treatment was sufficient to maximise yield.

At Myling, winter crops have dominated the site's history, with 6 crops. Winter cereal grain yield was increased in 1996 (Fig. 2*a*), 1999 (Fig. 2*d*), and 2001 (Fig. 2*g*), was reduced in 2000 (Fig. 2*e*), and showed no effect in 2004 (Fig. 2*i*). Only one winter cereal was sown after a long fallow. The 1996 wheat crop (Fig. 2*a*) had a highly significant response (Table 8) but with a relatively small yield gain of 370 kg/ha (7%) in the 90 kg N/ha treatment. The nil N treatment yielded 5540 kg/ha. Two short-fallow wheat crops were sown in 2000 and 2004. Yield was decreased with N application by 420 kg/ha in 2000 (Fig. 2*e*), an 11% reduction. Yield in 2004 (Fig. 2*i*) was not altered by N treatment. Double cropping showed significant responses in both sowings. Wheat in 1999 (Fig. 2*d*) produced a 1580 kg/ha grain yield increase with the first 30 kg N/ha treatment. The second 30 kg N/ha applied added 380 kg/ha of grain. The 2001 barley (Fig. 2*g*) double cropped into mungbean stubble gained 1220 kg/ha with 30 kg N/ha (55%). Yield was depressed at high N fertiliser rates (90 and 120 kg N/ha); however, this may have also been due to the phytotoxic effects of herbicide application at those phenology stages.

Summer crop grain yield responses to N

At Colonsay, sorghum was the dominant crop with 5 crops on long fallow and 5 on short fallow. Long-fallow sowings were in 1986 (Fig. 1*b*), 1991 (Fig. 1*g*), 1994 (Fig. 1*j*), 1997 (Fig. 1*l*), and 2001 (Fig. 1*o*). N application improved yield in 1986 and 2001, and had no effect in the remaining 3 years. Forty kg N/ha increased grain yield by 590 kg/ha in 1986 and 670 kg/ha in 2001, increases of 16 and 13%, respectively. Higher rates had no additional effect. Short-fallow crops were sown in 1987 (Fig. 1*c*), 1988 (Fig. 1*d*), 1989 (Fig. 1*e*), 1998 (Fig. 1*m*), and 1999 (Fig. 1*n*), each with highly significant N responses (Table 7). In 1987, 80 kg N/ha maximised grain yield with an increase of 2630 kg/ha (117% increase). The remaining years (1988, 1989, 1998, and 1999) responded to increasing N rate up to the 120 kg N/ha treatment. Grain yield increases greater than 3000 kg/ha were recorded in each with the highest rate of N application. Average incremental grain yield increases in the 5 short-fallow sorghum crops were 1440 kg/ha (range 840–1860 kg/ha), 1220 kg/ha (range 610–2050 kg/ha), and

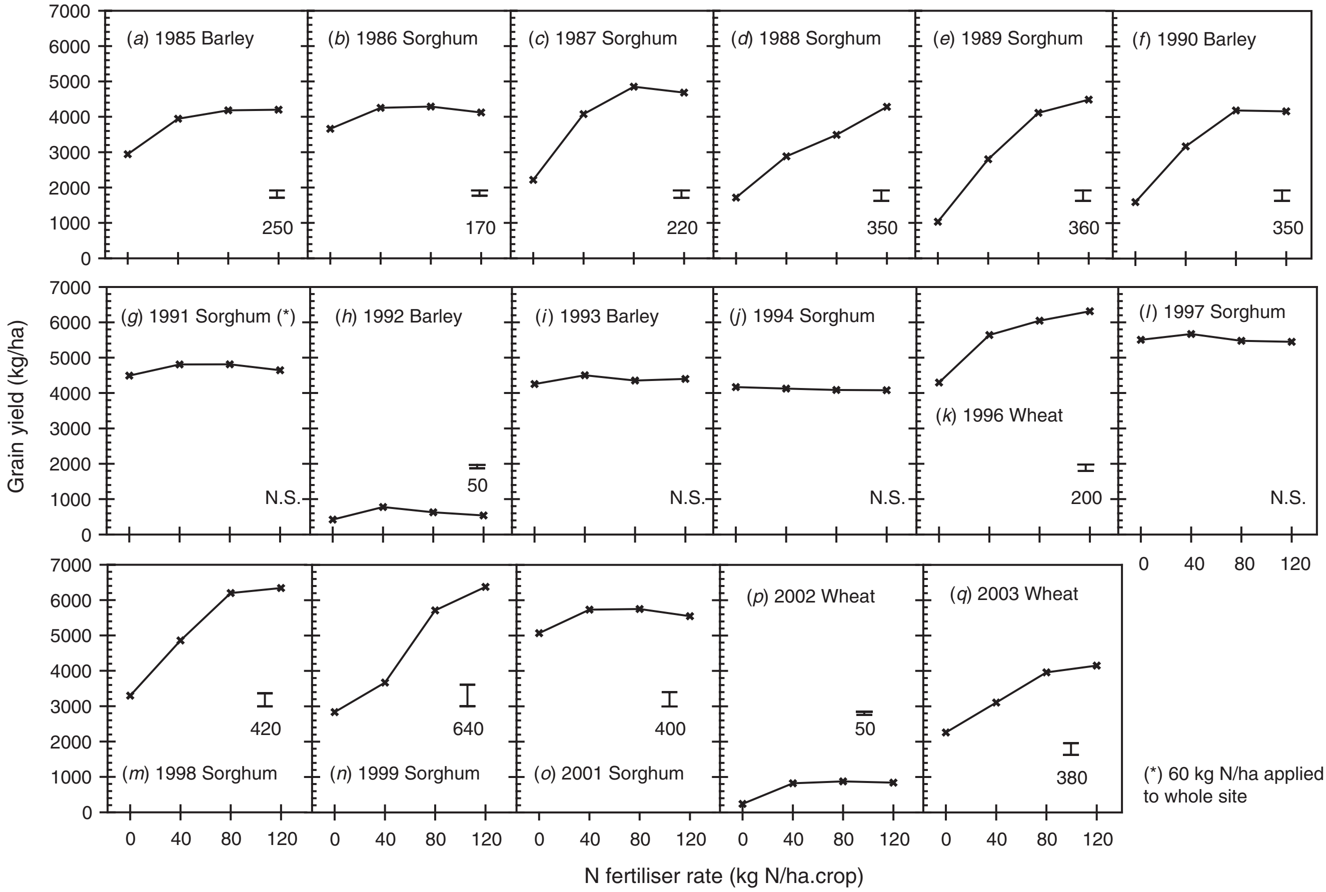

Fig. 1. Grain yield responses to 4 N fertiliser treatments at Colonsay, Darling Downs, Qld, from 1985 to 2003. Vertical bars indicate l.s.d. ($P = 0.05$) for comparing N rates; N.S., no significant difference ($P > 0.05$).

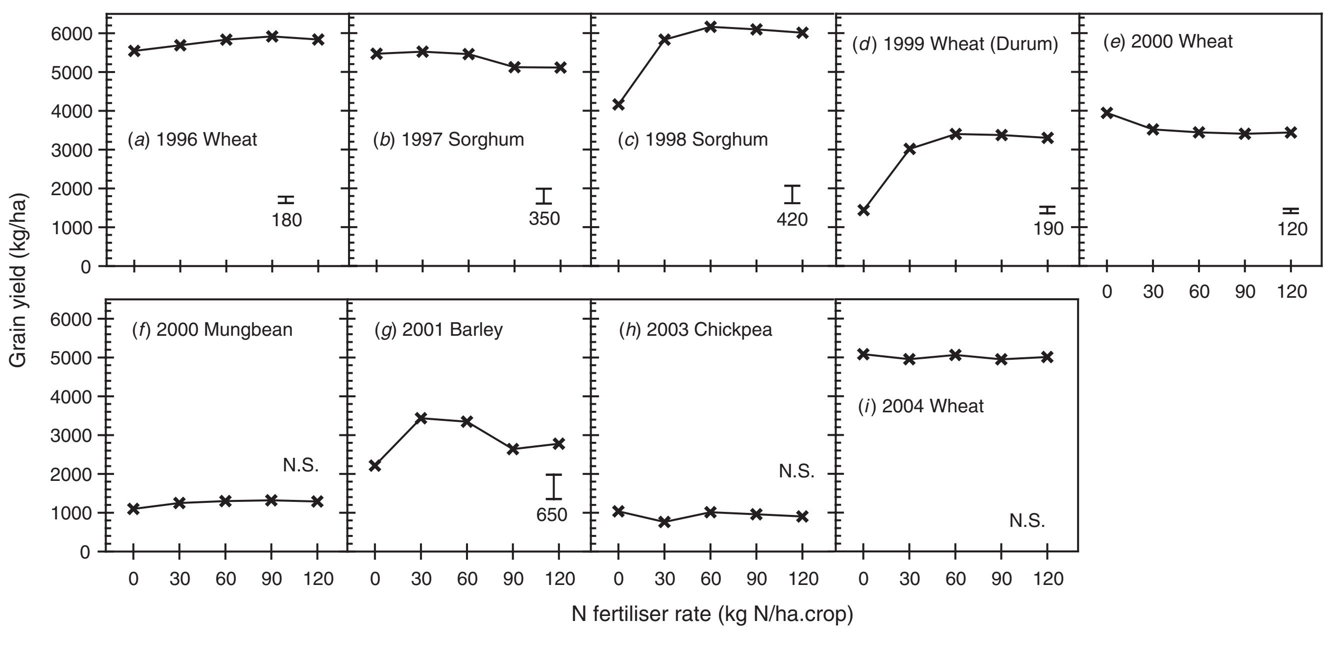

Fig. 2. Grain yield responses to 5 N fertiliser treatments at Myling, Tulloona, NSW, from 1996 to 2004. Vertical bars indicate l.s.d. ($P = 0.05$) for comparing N rates; N.S., no significant difference ($P > 0.05$).

350 kg/ha (range –170 to 790 kg/ha) for the first, second, and third increments of 40 kg fertiliser N/ha, respectively.

The grain yield from treatments with no N declined during periods of continuous summer cropping. From 1986 (Fig. 1*b*) to 1989 (Fig. 1*e*), nil N grain yield declined from 3660 kg/ha to 1010 kg/ha, and from 1997 (Fig. 1*l*) to 1999 (Fig. 1*n*), nil N grain yield declined from 5500 kg/ha to 2830 kg/ha. Similar % yield reductions have occurred in both periods with the second crop yielding 60% of the first, and the third crop 50% of the first.

At Myling, 2 sorghum crops were sown in 1997 (Fig. 2*b*) after long fallow, and a short-fallow crop in 1998 (Fig. 2*c*). In 1997, N rates above 60 kg N/ha depressed grain yield by 350 kg/ha (6%). In 1998, 30 kg N/ha significantly increased yield by 1670 kg/ha (40%), and maximised yield at 60 kg N/ha with a 2000 kg/ha gain (48%) compared with nil. The uninoculated mungbean crop in 2000 (Fig. 2*f*) showed no N treatment effect.

Agronomic efficiencies of nitrogen

At Colonsay, AE_N ranged from just below zero to nearly 50 kg grain/kg fertiliser N applied (Fig. 3). Ten of 17 harvested crops had AE_N for the first 40 kg N above 20 kg grain/kg fertiliser N applied. Responses in long-fallow summer crops were generally small, <20 kg grain per kg N applied, while long-fallow winter crops, short-fallow summer crops, and double-cropped winter cereals had higher AE_N. Only during the drought period from 1991 (Fig. 3*g*) to 1994 (Fig. 3*j*) were responses essentially nil.

The highest average AE_N was from short-fallow sorghum crops where over the 5 crops (Fig. 3*c*, *d*, *e*, *m*, *n*), AE_N was 36, 33, and 25 kg grain/kg fertiliser N applied for the 40, 80, and 120 kg fertiliser N/ha rates. The 1999 sorghum crop (Fig. 3*n*) indicated a higher AE_N for the 80 and 120 kg N rate over the 40 kg N application and this may have been influenced by herbicide damage co-variate analysis.

Long-fallow winter cereals had AE_N above 20 kg grain/kg fertiliser N for the first 40 kg N applied for both years (Fig. 3*a*, *k*). Short-fallow and double-crop winter cereals ranged from generally nil to 15 kg AE_N (Fig. 3*h*, *i*, *p*), to above 15 kg AE_N (Fig. 3*f*, *q*).

At Myling, fallow type appears to have been a less significant factor in N responsiveness, with the scale of N response in general being small. Responses to fertiliser N have occurred following periods of high cropping intensity (i.e. double cropping) or periods of reduced N mineralisation potential. AE_N was greater than 20 kg grain/kg fertiliser N for the first rate of N applied for only 3 crops: short-fallow sorghum in 1998 (Fig. 4*c*), double-cropped wheat in 1999 (Fig. 4*e*), and double-cropped barley in 2001 (Fig. 4*g*). For

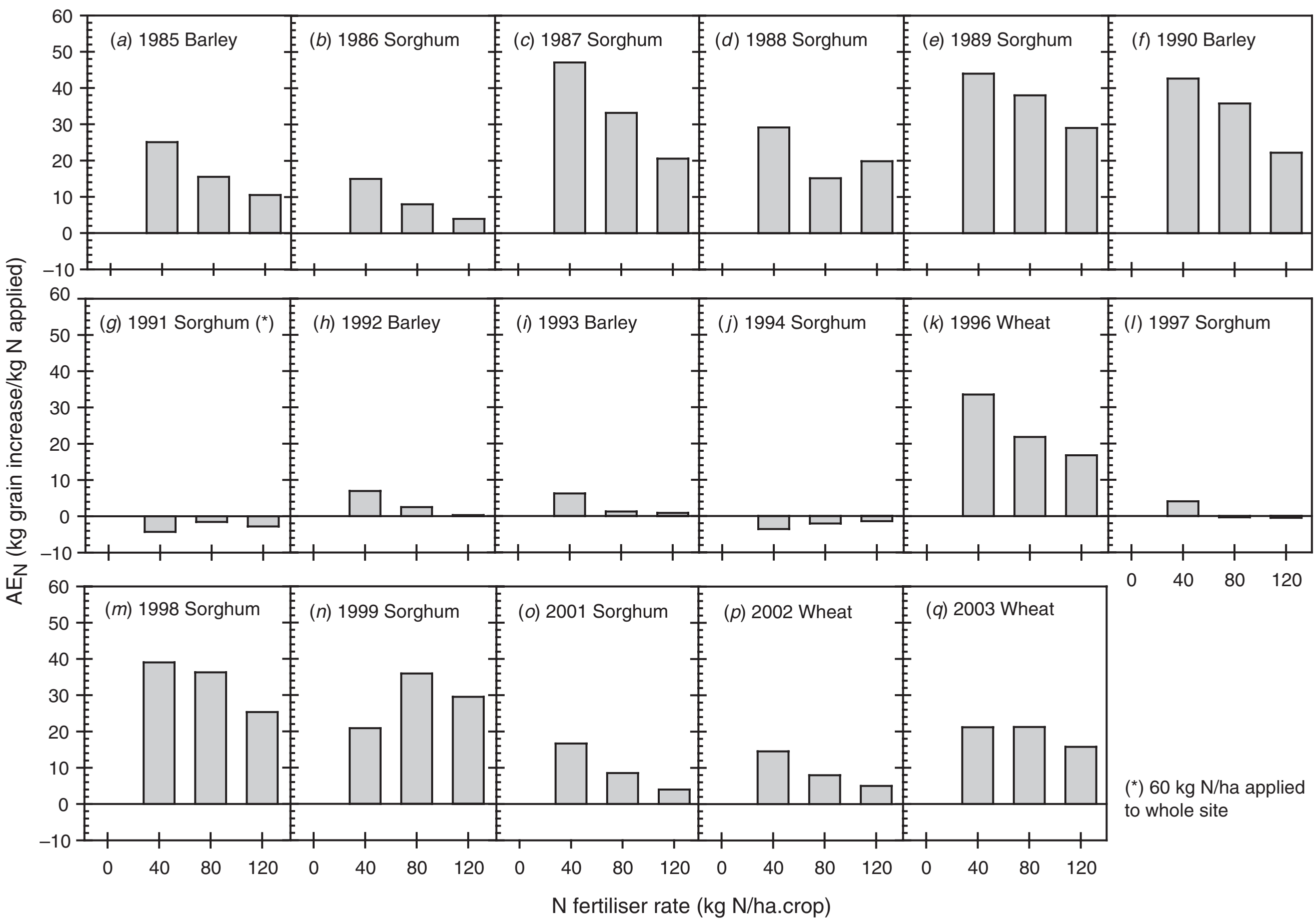

Fig. 3. Agronomic efficiency of N for fertiliser N treatments at Colonsay, Darling Downs, Qld, from 1985 to 2003.

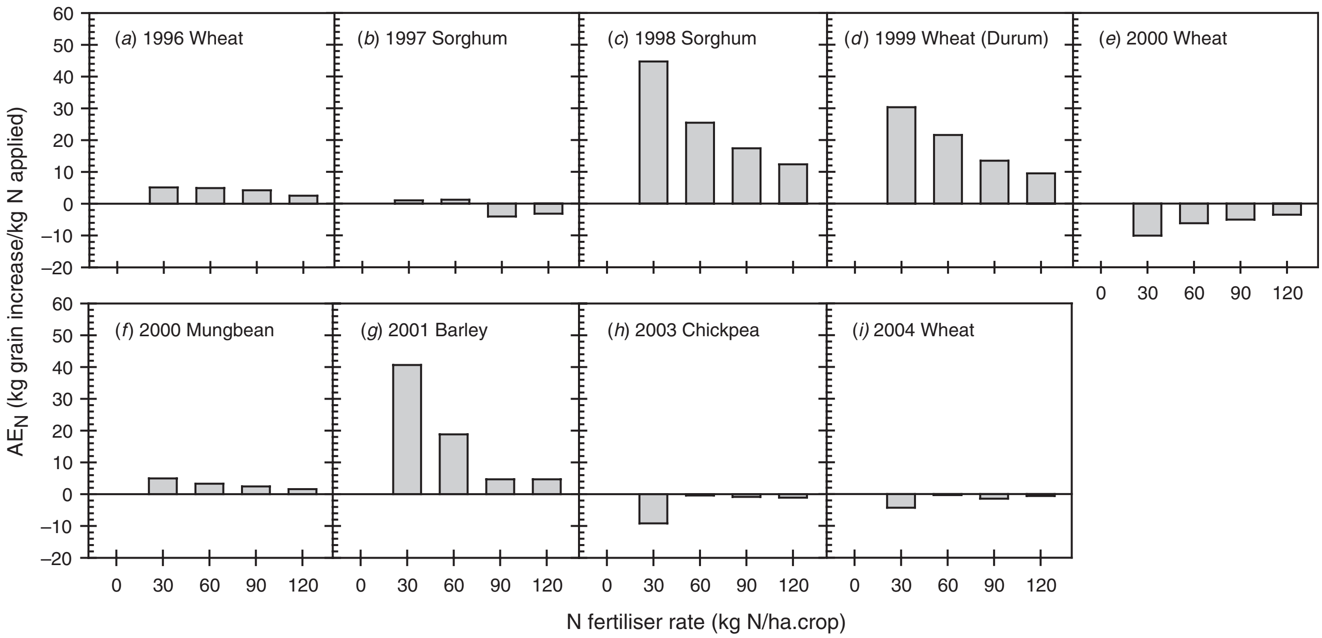

Fig. 4. Agronomic efficiency of N for fertiliser N treatments at Myling, Tulloona, NSW, from 1996 to 2004.

these 3 crops the 60 kg N fertiliser rate was also near 20 kg grain/kg fertiliser N. AE_N for the remaining crops was within a range of ± 10 kg grain/kg fertiliser N applied.

Phosphorus fertiliser responses

Grain yield increases at both sites indicate general reliability of fertiliser P response in winter crops, as expected from the available P concentrations, and long-fallow sorghum (Figs 5, 6). P fertiliser significantly influenced 9 of 17 harvested crops (Table 7) at Colonsay, 6 in winter cereals and 3 long-fallow sorghum crops. Only one winter cereal crop failed to respond to P from 7 sowings. At Myling, significant P effects occurred in winter cereals (3 crops), grain legumes (2), and long-fallow sorghum (1) (Table 8). Grain sorghum was non-responsive in short fallows, with none of 6 short-fallow crops in total sown at both sites recording a significant P effect.

Winter crop grain yield responses to P

At Colonsay, all but one winter cereal crop responded to P treatment, with barley in 1985 (Fig. 5*a*) the only crop that did not respond to P fertiliser. Barley sown in 1990 (Fig. 5*f*), 1992 (Fig. 5*h*), and 1993 (Fig. 5*i*) responded, as did wheat in 1996 (Fig. 5*k*), 2002 (Fig. 5*p*), and 2003 (Fig. 5*q*). Barley in 1993 and wheat in 2003 each increased grain yield by 600 kg/ha (20%) in the 10 kg P/ha treatment. In 1993 (Fig. 5*i*) an additional 200 kg/ha grain yield was gained under the 20 kg P/ha treatment. Wheat in 1996 (Fig. 5*k*) was the only responsive long-fallow crop sown. Grain yield was increased by 330 kg/ha (6%) in the 10 kg P/ha treatment and did not increase with higher P rate treatments. Three winter cereal crops were double cropped and all had highly significant P treatment effects. Barley was sown in 1990 (Fig. 5*f*) and 1992 (Fig. 5*h*), and wheat in 2002 (Fig. 5*p*). Yield was increased by 810 kg/ha (31%) under the 10 kg P/ha treatment in 1990 (Fig. 5*f*). Smaller but significant responses occurred in 1992 and 2002. Average yield gain in the 10 kg P/ha treatment was 480 kg/ha (range 220–1050 kg/ha) from all winter cereal sowings.

At Myling, P fertiliser treatment significantly increased grain yields in 4 of 6 winter crops, chickpea in 2003 (Fig. 6*h*) and cereals in 1999 (Fig. 6*d*), 2000 (Fig. 6*e*), and 2004 (Fig. 6*i*). Chickpea grain yield was increased by 190 kg/ha (25%) in the 10 kg P/ha treatment (Fig. 6*h*). In the double-cropped wheat sown in 1999 (Fig. 6*d*), the largest yield increase was 180 kg/ha (6.5%) from the 20 kg P/ha treatment. Cereal grain yield was increased by 210 kg/ha (6%) and 570 kg/ha (12%) with 10 kg P/ha treatment in wheat sown in 2000 (Fig. 6*e*) and 2004 (Fig. 6*i*). P treatments at 20 kg P/ha did not further enhance grain yield in those crops. No P response occurred in 1996 with wheat (Fig. 6*a*) or in 2001 with barley (Fig. 6*g*).

Summer crop grain responses to P

At Colonsay, long-fallow durations increased P response frequency. Three of 5 sorghum crops sown following long fallow recorded significant P responses, with average yield increases of 180 kg/ha (range –40 to 520 kg/ha) from the 5 crops. The 10 kg P/ha.crop treatment increased grain yield by 200 kg/ha in 1986 (5%) (Fig. 5*b*), 250 kg/ha in 1997 (5%) (Fig. 5*l*), and 520 kg/ha in 2001 (9%) (Fig. 5*o*). Yield increased further with 20 kg P/ha treatment in 1986 (200 kg/ha) and 1997 (135 kg/ha). The sowings in 1991 and 1994 indicated no effect (Fig. 5*g*, *j*) from P treatment. No responses to P were recorded in short-fallow grain sorghum from 5 sowings.

At Myling in 1997 (Fig. 6*b*), 610 kg/ha yield was gained at the 10 kg P/ha treatment, a 12% increase. The sorghum crop planted

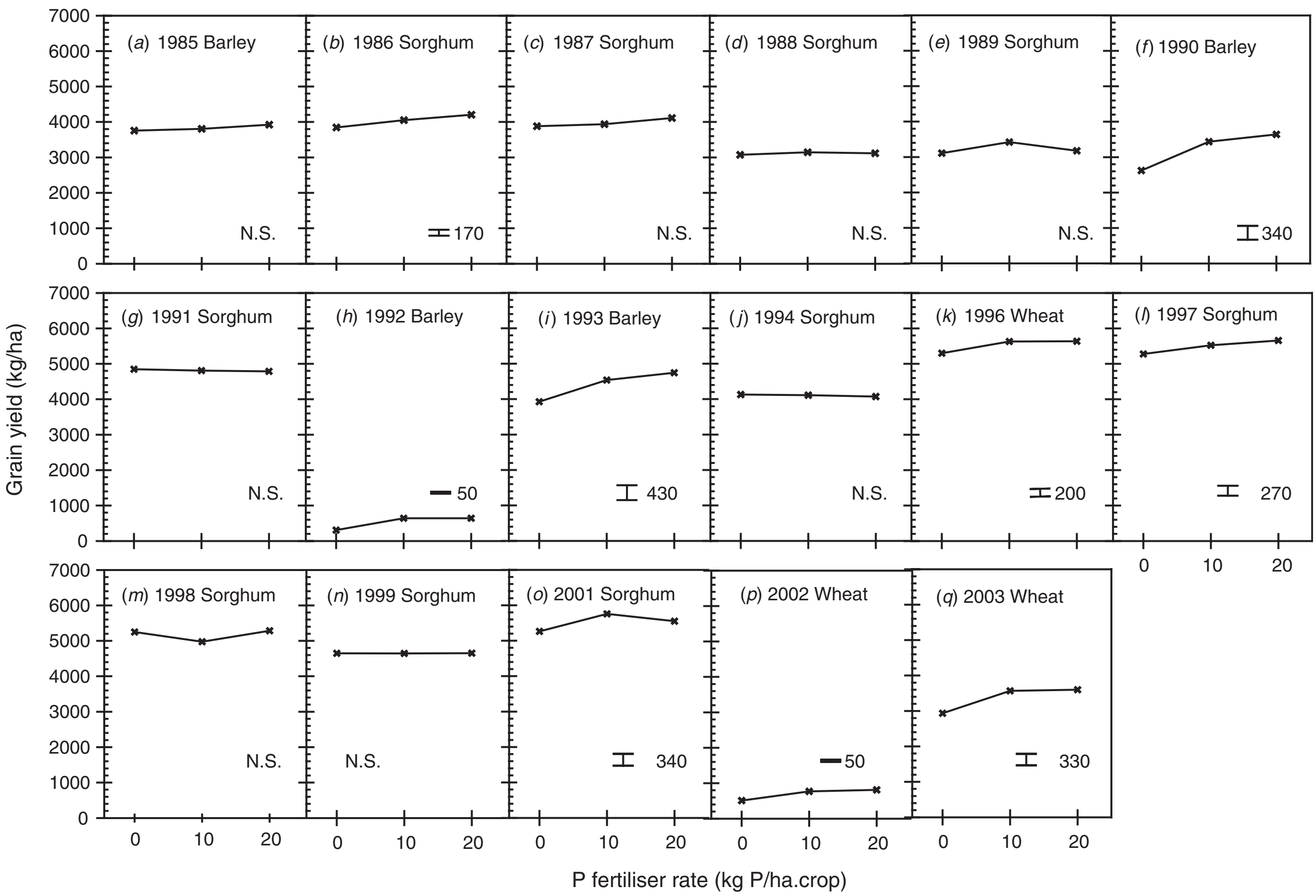

Fig. 5. Grain yield responses to 3 P fertiliser treatments at Colonsay, Darling Downs, Qld, from 1985 to 2003. Vertical bars indicate l.s.d. ($P = 0.05$) for comparing P rates; N.S., no significant difference ($P > 0.05$).

the following year did not respond (Fig. 6*c*). Mungbean in 2000 significantly responded to P treatments with increases of 150 kg/ha (14%) and 260 kg/ha (25%) grain in the 10 kg P/ha and 20 kg P/ha treatments (Fig. 6*f*).

Discussion

Effect of cultivation age on fertiliser response

Age of cultivation and cropping intensity influenced the number and size of the responses to N and P fertiliser inputs. Dalal and Mayer (1986*a*) described the decrease in winter cereal yields with increasing cultivation age for key cropping soils of southern Queensland. The change in land use has led to a reduction in organic C and N contents, resulting in a depletion of N supply for crop growth. For Waco soils (black Vertosols), Dalal (1989) and Dalal and Mayer (1987) outlined the loss of mineralisable N from 98 kg N/ha in the first year of cultivation, to 50 kg N/ha in the 15th, to an equilibrium level after 40 years of 37 kg N/ha. Dalal (1989) indicated the significance of maintaining or restoring N-supplying capacity if crop yield and quality are to be maintained. Strong (1990) reported that an increasing period of cultivation and cropping influences the amount of soil nitrate-N (0–0.60 m) accumulated before sowing under differing fallow lengths, from over 217 experiments on the Darling Downs. The findings were that soils cropped for more than 10 years accumulated nitrate-N at similar rates, but that on average, long-fallow had 35% more nitrate-N than summer-autumn fallowing.

Winter and summer crop grain yield responses at Colonsay (Table 7, Figs 1 and 3), indicate the general benefit of fertiliser N application on soils with reduced mineralisation capacity. N responses were larger and more consistent in short-fallow and double-crop sowings, rather than the extended long fallow, which allows greater accumulation of mineralised N. When the experiment commenced in 1985, it was following a period of 45 years of cultivation. Applications of N on new cultivation ground with higher supplies of mineralisable N, such as the Myling site, showed few large grain yield responses to N, with any significant increase generally limited to the first 30 kg N/ha in situations of high cropping intensity. The Myling site is at the 20-year point since conversion from pasture and, from the studies of Dalal and Mayer (1987), should be at the transition point to the lower nitrogen mineralisation equilibrium potential, indicating greater probability of responding to fertiliser N inputs.

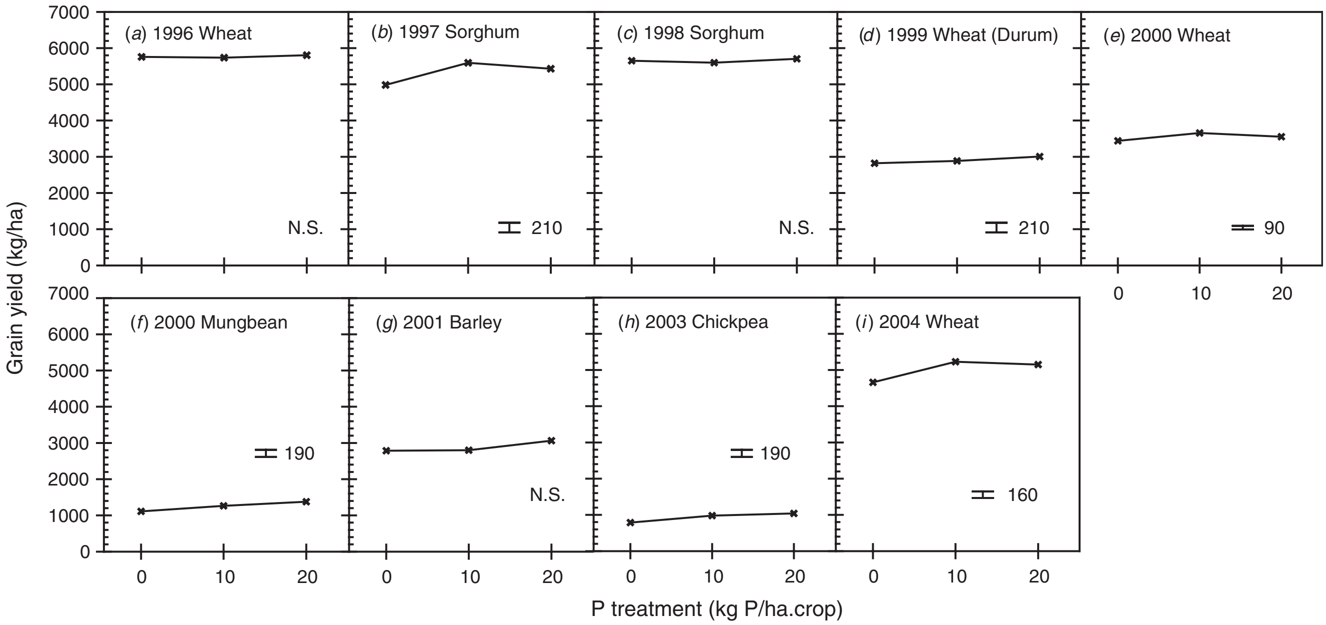

Fig. 6. Grain yield responses to 3 P fertiliser treatments at Myling, Tulloona, NSW, from 1996 to 2004. Vertical bars indicate l.s.d. ($P = 0.05$) for comparing rates; N.S., no significant difference ($P > 0.05$).

N and P are independent nutrients

The results from the Colonsay and Myling experiments support the findings that overall, N and P are nutrients that have little interaction, for not only winter cereals but for most grain crops on soils of this type in the northern grains region. This is in concurrence with many authors who have researched N × P fertiliser effects on winter cereal grain yields (Colwell and Esdaile 1968; Hibberd *et al*. 1969; Rasmussen *et al*. 1972; Whitehouse 1972; Strong *et al*. 1978; Holford and Cullis 1985; Holford and Doyle 1992*b*; Holford *et al*. 1992) where the majority of reported studies demonstrate few interactions at optimal nutrient levels. Fewer studies have been conducted on sorghum and other summer cereals, but they too indicate independence of N and P effects on grain yield. This contrasts with several sorghum studies on Vertosols in India, which report responses to the combination of N and P fertilisers (Katayama *et al*. 1999; Ghosh *et al*. 2003). Within the northern grains region, N and P can be managed independently of one another.

Management strategies for fertiliser N use on soils of differing cultivation age

Responses to N were larger and more consistent on the old cultivation site than on the relatively recently cleared area. For both cultivation ages, long fallowing into either winter or summer cereals required less fertiliser N to achieve maximum yields compared with short fallowing. For sorghum at the old cultivation site (Colonsay), application of N fertiliser up to 40 kg N/ha was sufficient to maximise grain yield for long-fallow sowings. No grain yield response to N application was recorded in the younger cultivation area (Myling). Winter cereal sown following long fallow was responsive up to 80 kg N/ha at Colonsay.

N management becomes more critical to achieving maximum grain yields in short-fallow systems on old cultivation areas. At Colonsay, fertiliser applications between 80 and 120 kg N/ha maximised short-fallow sorghum, wheat, or barley yields in most years; however, rates above 120 kg N/ha may have been beneficial for some sorghum crops. The application rates to wheat are at the upper end of the range suggested by Strong *et al*. (1996*b*). In a study on a fertility-depleted Vertosol with continuous wheat from 1987 to 1994, they reported that N fertiliser significantly increased grain yield in all but one year, where N rates of 25–75 kg N/ha usually raised grain yield to its optimum. When analysing the effects of successive N applications in a continuous wheat system (Strong *et al*. 1996*a*), 50 kg N to each crop appears to be more profitable when the price of high-protein grades has only a low to moderate return relative to low protein. Holford *et al*. (1992) and Holford and Doyle (1992*a*), reporting on 58 factorial N × P fertiliser experiments with wheat across the northern slopes and plains of New South Wales from 1985 to 1989, found that 70% of sites responded to N fertiliser application. To reach 90% maximum yield, 23 required more than 60 kg N/ha and more than half required more than 30 kg N/ha. Strong and Holford (1997) reported that the frequency of grain yield response to fertiliser N appears to be inversely related to grain protein concentration, using data of Strong (1990) and Holford and Doyle (1992*b*). Wheat crops with protein below 11.5% demonstrated yield responses to fertiliser N in 90% of cases in Queensland. Kelly *et al*. (2004), in a probability analysis, found that the 90% likelihood of a deficiency in N supply for wheat and barley is predicted by a grain protein of <11.5% and <11%, respectively. For all winter cereal crops at both sites, these criteria held in predicting yield response from grain protein.

Holford *et al*. (1997) assessed a total of 40 sites on the north-western slopes and plains for N supply adequacy for sorghum, using 5 N rates, from 1989–90 to 1991–92. Their conclusion was that N deficiency is widespread in the cereal-growing soils of northern NSW. The study had mostly long-fallow crops from wheat, 7 short fallow, and one double crop. Crops grown generally north of 30°30′S (line from Narrabri to Walgett) had higher starting soil N levels and hence were less responsive to fertiliser N. For areas south of this, grain yield was increased generally up to the 80 kg N/ha rate; however, responses were influenced by soil N levels, and the amounts of fallow, pre-flowering, and post-flowering rainfall. Holland and Herridge (1992) reported almost linear grain yield responses to N fertiliser up to 100 kg N/ha in sorghum short fallowed from a previous sorghum crop at a low-fertility site on the Liverpool Plains. Dowling and Vaschina (1996) suggested a critical protein for sorghum of 9.5%. The 90% likelihood of a deficiency in N supply for sorghum (Kelly *et al*. 2004) is predicted by a grain protein of <9%. This decreases to a 60% likelihood for protein between 9 and 10%. These criteria held for 11 of 12 sorghum crops at both sites.

Management strategies for use of P fertilisers

Grain yield response to fertiliser P is influenced by species sensitivity to soil P supply and vesicular arbuscular mycorrhiza (VAM) levels. Increasing fallow length reduces VAM levels (Thompson 1987) and can lead to the expression of long-fallow disorder in crops, such as chickpea, mungbean, and sorghum, with high mycorrizhal dependency (Thompson *et al*. 1997). Wheat and barley have been classified as having low and very low mycorrizhal dependency, respectively (Thompson *et al*. 1997). There has been extensive investigation of winter cereal response to P application in the northern grains region (Colwell and Esdaile 1968; Hibberd *et al*. 1969; Whitehouse 1972; Strong *et al*. 1978; Holford and Doyle 1993), but less so for sorghum (Hibberd *et al*. 1991*a*; Strong 1998; Moody and Bolland 1999). Chisholm and Strong (1984), in reporting critical soil test values for P response in wheat across the Darling Downs, stated that Colwell P less than 15 mg/kg was responsive for all sites.

Many authors suggest that 10–12 kg P/ha is the most economic rate for wheat across an area covering the north-west slopes and plains, south-western downs, Western Downs, Maranoa, and the Central Highlands (Colwell and Esdaile 1968; Hibberd *et al*. 1969; Strong *et al*. 1978; Holford and Doyle 1993), with yield gains of 300 kg/ha on average to P fertiliser (Strong and Holford 1997). Further research by Strong *et al*. (1997), which studied the effects of repeated annual application on 2 soils representative of the Western Downs, Qld, reports that annual P applications at low rates (4 or 8 kg/ha) banded near the seed created profitable responses over the sequence of successive wheat crops from 1978 to 1988.

Winter cereals grown at the Colonsay and Myling sites showed similar results. Significant P responses occurred in 5 of 7 winter cereals sown either on long or short fallow, 10 kg P/ha treatment producing the largest yield increment. All short-fallow and double-crop winter cereals at Colonsay responded to P treatment, with no response in the one long-fallow crop. Similar trends occurred at Myling, with no response to P in the long-fallow winter cereal, both short-fallow crops responding to P, and one of 2 double-crop sowing responding. These results are consistent with the results of Best *et al*. (1982) and Chisholm and Strong (1984) as both Colonsay and Myling are <15 mg/kg Colwell-P for the 0–0.10 m layer.

Sorghum sown following a long fallow responded significantly to P treatments in 4 of 6 sowings at both sites (Tables 7 and 8, Figs 5 and 6). The 10 kg P/ha treatment was generally sufficient for improved yields, although in 2 crops at Colonsay in 1986 (Fig. 5*a*) and 1997 (Fig. 5*d*), yield was increased further at the 20 kg P/ha treatment. None of 6 sorghum crops at either site sown on short fallow from sorghum in the previous year responded to P application (Tables 7, 8). This is a similar result to work of Hibberd *et al*. (1991*b*) in central Queensland, who in a 5-year study only recorded P responses in sorghum after an 18-month-long fallow. They attributed the lack of responsiveness in short-fallow crops to VAM levels. Sahrawat *et al*. (1995), in a study on a very low-P Vertosol in India (0.4 mg/kg Olsen), reported very high yield responses to P application up to 40 kg P/ha in a sequence of 3 sorghum crops. The higher P rates were required due to a high P buffering capacity (Sahrawat and Warren 1989). Results from the Colonsay and Myling sites suggested that northern grains-region growers can be encouraged to consider P application for sorghum sown on long fallow in reasonable anticipation of a yield benefit. Strong (1998) suggests in summary that where soil test P values are low, P should be applied to sorghum and barley crops. Strong (1998) also notes that early growth responses in mungbean and chickpea suggested that grain yield responses may occur less frequently than for cereals.

The implications of a maintenance or replacement P application under non-responsive yield conditions are yet to be fully investigated. For example, from this dataset, P application on short-fallow sorghum crops has not indicated a yield benefit; however, other crop management factors, such as ensuring even flowering and hence lower exposure to insect damage from sorghum midge, may be gained from P application.

Conclusions

As many of the soils in the northern grains region continue to age from the time they were converted from livestock-based systems, the Colonsay site will allow further investigation into N and P fertiliser application for summer and winter crop production. Producers using older cultivation soils can expect input of N and/or P fertilisers to provide grain yield responses under most conditions. The Myling site with its shorter timeframe since the change of land use, allows a further insight into the decline of native fertility. Yield responses to N and P fertilisers over the history of the sites were predominantly in agreement with those obtained under single-year experiments. Response predictions of grain protein levels for N supply, Colwell-P soil test values, likely VAM levels from previous crop, and fallow length are supported by these long-term datasets. These research sites have histories of both winter and summer crop production differentiating them from other long-term experiments that focused on one or the other. These differing cropping systems may alter nutrient behaviour in the soil. Integration of a crop N supply (soil N and applied fertiliser N) with soil water and crop growth models would allow further investigation of the interaction effects of N supply, soil moisture, and growing-season rainfall on grain production.

Further examination of the recovery of fertiliser N and P in grain, the balance of soil N, P, and carbon, and the potential economic effects of fertiliser application will be reported in subsequent papers.

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