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Fertiliser N and P application on two Vertosols in north-eastern Australia. 3. Grain N uptake and yield by crop/fallow combination, and cumulative grain N removal and fertiliser N recovery in grain

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Abstract. The grain N uptake response of an opportunity cropping regime comprising summer and winter cereal and legume crops to fertiliser nitrogen (N) and phosphorus (P) applications was studied in 2 long-term experiments with contrasting durations of cultivation. At the longer cultivation duration Colonsay site (>44 years at commencement), grain N uptake increased with fertiliser N application in 15 of 17 harvested crops from 1985 to 2003. Grain sorghum on short-fallow consistently responded to applied fertiliser N at higher rates ($\geq$80 kg N/ha) than crops grown on long-fallow where either fertiliser at nil or 40 kg N/ha maximised grain N uptake. Winter cereal response to applied N was influenced by fallow length, generally smaller responses in long fallow years, although in-crop rainfall affected this. Short-fallow crops responded up to 40 or 80 kg applied N/ha, while seasonal growing-season rainfall affected the responses of the double-crop winter cereals the most. Responses to applied fertiliser N at the shorter duration cultivation Myling site (9 years at commencement) generally occurred only under high-intensity cropping periods, or in those crops sown following periods of slower potential N mineralisation. Phosphorus fertiliser application influenced grain N uptake at both locations in some years, with winter cereals, legumes, and sorghum sown following long-fallow generally significant.

Cumulative grain N uptakes in both experiments were independently influenced by fertiliser N and P treatments, P having an additive effect, increasing grain yield and grain N removed. Recovery efficiency of fertiliser N in grain, derived from cumulative N fertiliser application and grain N uptake, in general declined as amount of fertiliser N applied increased; however, as N supplies became less limiting to yield, P fertiliser generated higher fertiliser N recovery in grain. At Colonsay, RE_{NG} from cumulative uptake and removal was $\geq$0.48 with fertiliser P application for cumulative fertiliser N input $\leq$1340 kg N/ha ($\approx$80 kg fertiliser N/ha.crop).

Additional keywords: sorghum, wheat, barley, chickpea, mungbean, nitrogen, phosphorus.

Introduction

The northern grains region consists of 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) and, within it, the duration of cultivation influences the responsiveness of a cropping soil site to fertiliser N input. 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). As duration of cultivation increases, soil total and organic carbon (C) (Dalal and Mayer 1986*a*) and total nitrogen (N) decrease until a new equilibrium level is reached (Dalal and Mayer 1986*b*). 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).

The nutrients most limiting to crop production in the northern grains region are N and P (Dalal and Probert 1997). After >30 years of cultivation duration, economic crop yields are not possible on some Darling Downs (southern Queensland) soils without the addition of fertiliser N (Dalal and Mayer 1986*b*). Consequently, growers apply N and P fertilisers to optimise grain production, but areas with shorter cultivation durations and still declining fertility may have different nutrient requirements from areas that have reached equilibrium at a lower nutrient status.

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Recent reports discussing the implication of fertiliser N usage on global food production and ecosystems have renewed focus on the effectiveness and sustainability of applying fertiliser N (Mosier *et al*. 2004; Ladha *et al*. 2005).

Agro-ecological conditions allow production of both summer and winter cereal, legume, oilseed, and fibre crops, with sowing primarily occurring once a sufficient soil water profile to mitigate risk of crop failure from insufficient plant-available water has been reached (Freebairn *et al*. 1997). Studies with fertiliser N and P in this system have generally focussed on the effectiveness of input before the current crop, with longer term experiments primarily investigating effects of the interaction among tillage, stubble cover, and N on winter cereal production occurring on Vertosols at Warra, Qld, in 1987–94 (Strong *et al*. 1996*b*), Hermitage station near Warwick, Qld, from 1969 onwards (Thompson 1989), and in south-western Qld near St George in 1996–2001 (Thomas *et al*. 2007). Few long-term experiments utilising an opportunity cropping system of both summer and winter crops have assessed the effects on grain N uptake of fertiliser N and P input within this production region.

This study assesses grain N uptake and grain yield response, together with a cumulative recovery efficiency of fertiliser N in grain N of both winter and summer crops under differing preceding fallow lengths at 2 long-term N × P fertiliser experimental sites with contrasting cultivation durations.

Materials and methods

Experimental site descriptions and crop agronomy

The long-term experimental sites were 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. Full descriptions of the sites along with details of crop agronomy and experimental procedures have been provided by Lester *et al*. (2008).

Briefly, the Colonsay experiment commenced in 1985 on a site that was first cultivated in 1944, >40 years before initiation of the experiment. The soil is a haplic, self-mulching, endohypersodic, black Vertosol (Isbell 1996) of the Norillee Series (Beckmann and Thompson 1960; Vandersee 1975). A factorial randomised complete block design with 3 replicates was used in which 4 rates of N (0–120 kg N/ha) as urea (46% N) and 4 rates of P (0–20 kg P/ha) as triple superphosphate (20.7% P) were applied to each crop. The N treatments additionally had a split-plot component. 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). Sulfur and zinc have been applied to lessen potential growth limits, while soil test levels of remaining nutrients were above critical levels. Growing-season rainfalls measured at the site, taken as November–March for summer crops and June–November for winter crops, were generally within range of historic values covering rainfall amounts for 50–90% of years (Clewett *et al*. 2003).

The Myling site was first cultivated in 1987 and the experiment commenced in 1996. The soil is a haplic, self-mulching, endohypersodic, black Vertosol (Isbell 1996). A factorial combination of 5 N rates (0–120 kg N/ha) and 3 P rates (0–20 kg P/ha) was applied to each crop, with treatments arranged in a randomised complete block design. Fertiliser N was applied pre-planting in a split-plot design as urea (46% N) or anhydrous ammonia (82% N). As with the Colonsay experiment, P was applied as a band of triple superphosphate. Colwell P (0–0.1 m) across the experimental area in 1996 was 19 mg/kg. Background levels of remaining nutrients were above critical levels. Growing-season rainfalls at the site were generally within range of values for 50–90% of years (Clewett *et al*. 2003).

Grain harvest and plant analysis

Mechanically harvested grain at each site was analysed for N concentration, except for 2 years at Colonsay where likely protein estimates were made from Holford *et al*. (1997) for sorghum, and from Birch *et al*. (1997) for barley. Grain N concentration was determined either using Kjeldahl digests followed by automated ammonium analysis (Crooke and Simpson 1971) or through near-infrared reflectance. Grain yield (kg/ha) and grain N uptake (kg N/ha) were calculated with adjustment to the maximum moisture level accepted for grain receival, *viz*. 12.0% moisture for mungbean, 12.5% for wheat and barley, 13.5% for sorghum, and 14% for chickpea.

Statistical analysis

ANOVA using orthogonal polynomial contrasts and mean separation using least significant differences (l.s.d.) at the 5% level were calculated using GENSTAT 10th Edn (Payne *et al*. 2007). All statistical presentation is at the 5% level of significance, unless otherwise stated. Reported seasonal mean grain N uptake (kg N/ha) and statistical effects are the main plot effects at nil, 10, and 20 kg P/ha.crop treatments.

Recovery efficiency of fertiliser nitrogen in grain

Ladha *et al*. (2005) defined recovery efficiency of fertiliser N in grain (RE_{NG}) as the ratio of grain N to fertiliser N, and in this study it is applied to the cumulative sums of grain N uptake and fertiliser N as:

$$RE_{NG} = (G_N - G_0)/(F_N - F_0) = \Delta G/\Delta N \text{ in kg/kg}$$

where G_N is cumulative grain N (kg N/ha) in the treatment with cumulative fertiliser N applied per plot (F_N, kg N/ha), and G_0 is cumulative grain N (kg N/ha) measured in the control treatment with the lowest cumulative fertiliser N applied (F_0, kg N/ha).

Results

N fertiliser effects on grain N uptake at the Colonsay site

Grain N uptake increased with fertiliser N in 15 of 17 crops covering a range of summer and winter cereals grown over varying fallow lengths (Fig. 1). Ten sorghum crops were harvested: 5 each on long (Fig. 1*b*, *g*, *j*, *l*, *o*) and short fallows (Fig. 1*c*, *d*, *e*, *m*, *n*). Three long-fallow crops (Fig. 1*b*, *l*, *o*) had grain N uptake and grain yield increases (ΔGY) which were generally largest with the first 40 kg fertiliser N/ha; however, further increases in grain N uptake occurred in 1986–87 (Fig. 1*b*) and 2001–02 (Fig. 1*o*) up to 80 kg fertiliser N/ha. Grain yield did not increase in either year. Fertiliser N had no

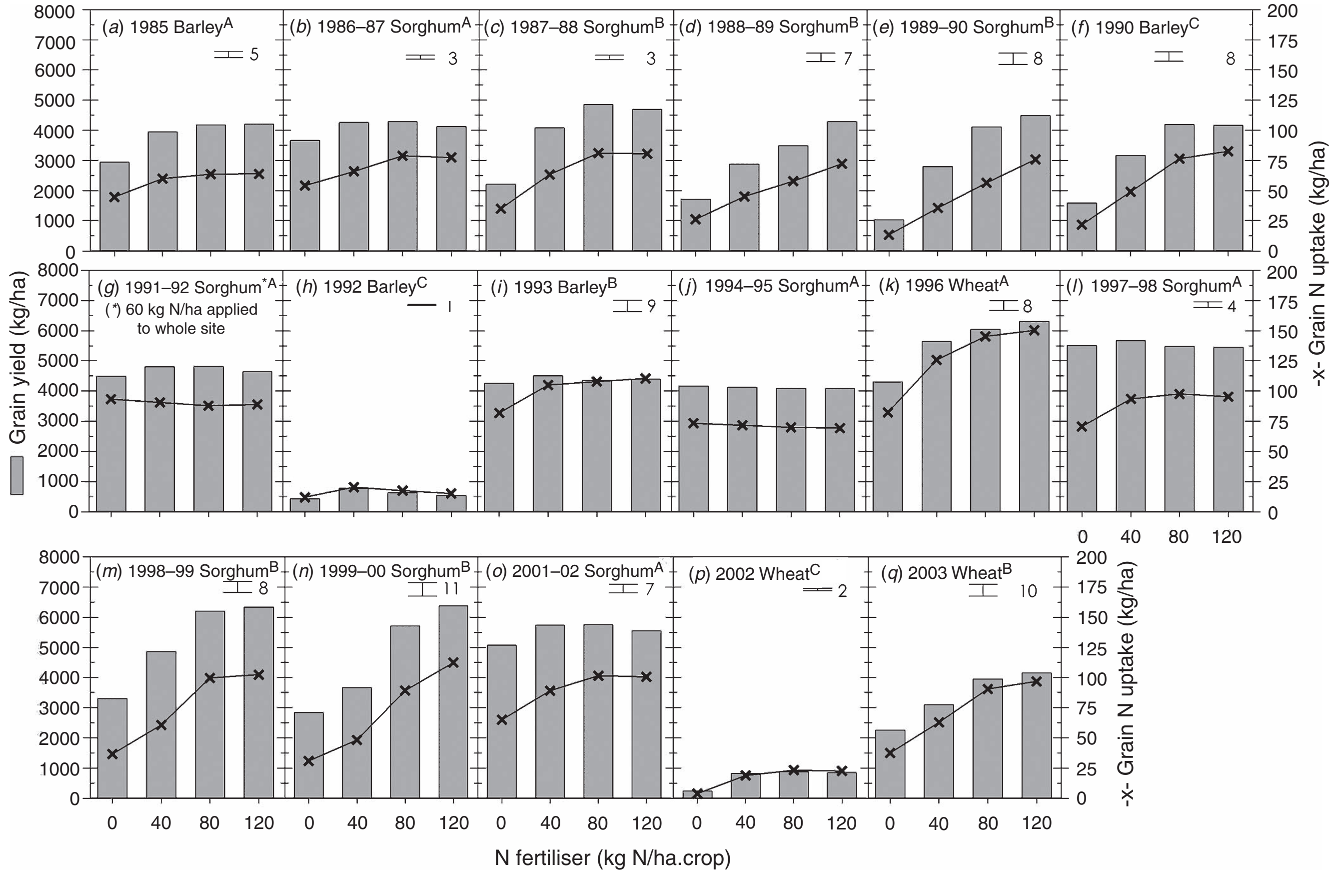

Fig. 1. Grain yield (kg/ha) and grain N uptake (kg N/ha) (×) at 4 N fertiliser rates at Colonsay, Darling Downs, Qld, in 1985–2003. Vertical bars are l.s.d. ($P = 0.05$) comparing grain N uptake with fertiliser N, blank if no significant difference ($P > 0.05$). [A], ~14 months fallow (long); [B], ~6 months (short); [C], <6 months (double).

effect on grain N uptake in 1991–92 (Fig. 1*g*) and 1994–95 (Fig. 1*j*).

Grain N uptake in the 5 short-fallow sorghum crops increased with the first 40 kg N/ha fertiliser by an average of 22 kg N/ha (range 17–28 kg N/ha; mean ΔGY +1400 kg/ha). There were differences in the grain N and yield response to the second 40 kg fertiliser N/ha (80 kg fertiliser N/ha rate) between crops sown in the 1980s (Fig. 1*c–e*) with mean grain N and yield increases of 17 kg N/ha and 900 kg/ha, and the late 1990s (Fig. 1*m*, *n*) with 39 kg N/ha and 1700 kg/ha, respectively. As the number of sorghum crops in sequence increased, grain N uptake at nil fertiliser N declined and fertiliser N response changed from curvilinear to linear (Fig. 1*b–e*, *l–n*). In 1986–87, grain N uptake with nil N was 54 kg N/ha, while after 4 sorghum crops in succession, 14 kg N/ha (1989–90) was taken up in grain N. Similarly, grain N uptake at nil N declined in 3 successive sorghum crops from 1997–98 to 1999–2000.

Seven winter cereals were harvested: 2 on long fallow (Fig. 1*a*, *k*), 2 on short fallow (Fig. 1*i*, *q*), and 3 double-cropped (Fig. 1*f*, *h*, *p*). Grain N uptake and yield increased in both long-fallow crops, up to 40 kg N/ha for 1985 barley (Fig. 1*a*), and 80 kg N/ha in 1996 wheat (Fig. 1*k*). For short-fallow crops, grain N uptake and yield were near maximum at the 40 or 80 kg fertiliser N/ha rates in 1993 (Fig. 1*i*) and 2003 (Fig. 1*q*). Of the 3 double-cropped winter cereals, 2 increases in grain N were relatively small under lower in-crop rainfall years (Fig. 1*i*, *p*), while the 1990 barley (Fig. 1*f*) under higher in-crop rainfall had the highest increase.

Phosphorus fertiliser effects on grain N uptake at Colonsay

Grain N uptake of 6 crops was affected by P fertiliser treatment at Colonsay (Table 1), with double-cropped and short-fallow winter cereals being most responsive. Responses were evident at 10 kg P/ha, with generally no further increase in N uptake with higher P rates. Increases in grain N for winter cereal crops were 7–16 kg N/ha. Grain N uptake response was significant in 2001–02 long-fallow sorghum, having 8 kg N/ha more with P applied than in the control. P fertiliser had no effect on the grain N uptake in the remaining 11 crops.

Cumulative grain yield, grain N uptake, and RE_{NG} at Colonsay

Fertiliser N and P independently increased cumulative grain yield ($P \leq 0.001$) and N uptake ($P \leq 0.001$), with no significant N × P interaction effect on either cumulative yield

Table 1. Grain N uptake (kg N/ha) of sorghum, wheat, and barley crops sown after ~14 months (long), ~6 months (short), or <6 months (double) fallow periods for 3 P fertiliser treatments at Colonsay, Darling Downs, Qld, in 1985–2003

n.s., Not significant

Crop season	Fallow length	Crop	P fertiliser rate (kg P/ha.crop) 0	10	20	l.s.d.
1985	Long	Barley	55	58	60	n.s.
1986–87	Long	Sorghum	68	68	69	n.s.
1987–88	Short	Sorghum	63	66	66	n.s.
1988–89	Short	Sorghum	51	51	52	n.s.
1989–90	Short	Sorghum	45	46	43	n.s.
1990	Double	Barley	51	60	59	7
1991–92	Long	Sorghum	95	88	92	n.s.
1992	Double	Barley	8	16	20	1
1993	Short	Barley	92	102	109	9
1994–95	Long	Sorghum	70	71	72	n.s.
1996	Long	Wheat	127	124	126	n.s.
1997–98	Long	Sorghum	86	88	92	n.s.
1998–99	Short	Sorghum	77	71	77	n.s.
1999–00	Short	Sorghum	73	68	70	n.s.
2001–02	Long	Sorghum	82	91	90	7
2002	Double	Wheat	12	19	20	2
2003	Short	Wheat	62	78	77	10

or grain N uptake. Cumulative grain yield and N uptake were lowest where cumulative fertiliser N input was 60 kg N/ha (Table 2). As the input of fertiliser N increased, P fertiliser was more influential on grain yield and N uptake. At a cumulative fertiliser input of 1340 kg N/ha (nominally 80 kg fertiliser N/ha.crop) and over, cumulative grain yield generally increased by 10% with fertiliser P input compared with the control.

Recovery efficiency of fertiliser N in grain (RE_{NG}) generally declined as N fertiliser applied increased (Table 2), with P application producing higher recoveries than no P at most N rates.

Nitrogen fertiliser effects on grain N uptake at Myling

Fertiliser N significantly affected grain N uptake in 7 of 9 crops at Myling (Fig. 2), with the largest increases in higher intensity crops, i.e. short-fallow sorghum in 1998–99 (Fig. 2*c*) and double-crop winter cereals in 1999 and 2001 (Fig. 2*d*, *g*). Uninoculated mungbean grain yield and grain N in 2000–01 (Fig. 2*f*) increased up to 30 kg fertiliser N/ha. Grain yield declined but grain N increased with increasing N input in the 2000 wheat crop (Fig. 2*e*). Although statistically significant, the grain N increases were small (≤15 kg N/ha) in long-fallow wheat in 1996 (Fig. 2*a*), following a forage sorghum in 1994–95, and long-fallow sorghum in 1997–98 (Fig. 2*b*). Two crops with no grain N uptake or yield response were chickpea 2003 (Fig. 2*h*) and wheat 2004 (Fig. 2*g*), where average uptake was 41 kg N/ha and 123 kg N/ha, respectively.

Phosphorus fertiliser effects on grain N uptake at Myling

Grain N uptake significantly increased with P fertiliser treatments in 4 of 9 crops, with no difference between 10 and 20 kg P/ha in P-responsive crops. Two wheat crops gained 5 and 12 kg grain N/ha with P application in 2000 and 2004 (Table 3), while long-fallow sorghum in 1997–98 and mungbean in 2000–01 also had increases.

Cumulative grain yield, grain N uptake, and RE_{NG} at Myling

Cumulative grain yield and N uptake were significantly influenced by both N ($P \leq 0.001$) and P fertiliser treatments ($P \leq 0.01$), with the N × P interaction not being significant. Grain yield, N uptake, and RE_{NG} were higher with application of P than without (Table 4), and as applied fertiliser N increased, RE_{NG} in grain declined.

Discussion

Effects of cultivation age and length of fallow on grain N uptake

The loss of mineralisable N with increasing cultivation age increases the potential requirement for N fertiliser to maintain productive capacity (Dalal 1989). At Colonsay, with its longer duration of cultivation (>44 years at commencement), fertiliser N application produced increasing grain yield and N uptake at rates ≥80 kg fertiliser N/ha for short-fallow lengths for winter and summer cereals (Fig. 1*d*, *e*, *f*, *k*, *n*, *q*). By contrast, at Myling (9 years at commencement), with a higher mineralisable N supply, yield and/or grain N responses occurred only under high-intensity, low N mineralisation cropping periods to

Table 2. Cumulative grain yield and grain N uptake, delta grain N, and recovery efficiency of fertiliser N in grain from plots with or without P application receiving differing amounts of N fertiliser application at the Colonsay experiment from 17 crops grown in 1985–2003

N fert. rate (kg N/ha.crop)	∑ N fert. applied[A] (kg N/ha)	Nil P ∑ Grain yield	∑ Grain N	Δ Grain N	RE_{NG}	Plus P ∑ Grain yield	∑ Grain N	Δ Grain N	RE_{NG}
0	60	49 210	760			48 860	740		
	220	52 620	830	70	0.44	54 710	840	100	0.63
40	700	64 070	1080	320	0.50	66 100	1060	320	0.50
	860	63 670	1110	350	0.44	68 850	1130	390	0.49
80	1340	68 370	1220	460	0.36	75 110	1360	620	0.48
	1500	68 940	1250	490	0.34	75 880	1370	630	0.44
120	1980	71 470	1350	590	0.31	75 040	1430	690	0.36
	2140	68 790	1310	550	0.26	76 190	1430	690	0.33

[A]60 kg N/ha was applied across the whole experiment in 1991–92. From barley in 1990 to sorghum in 1994–95 a split-plot regime of 'nil' or '+40' kg N/ha was implemented, increasing cumulative N fertiliser applied by 160 kg N/ha compared with the 'nil' N split-plot.

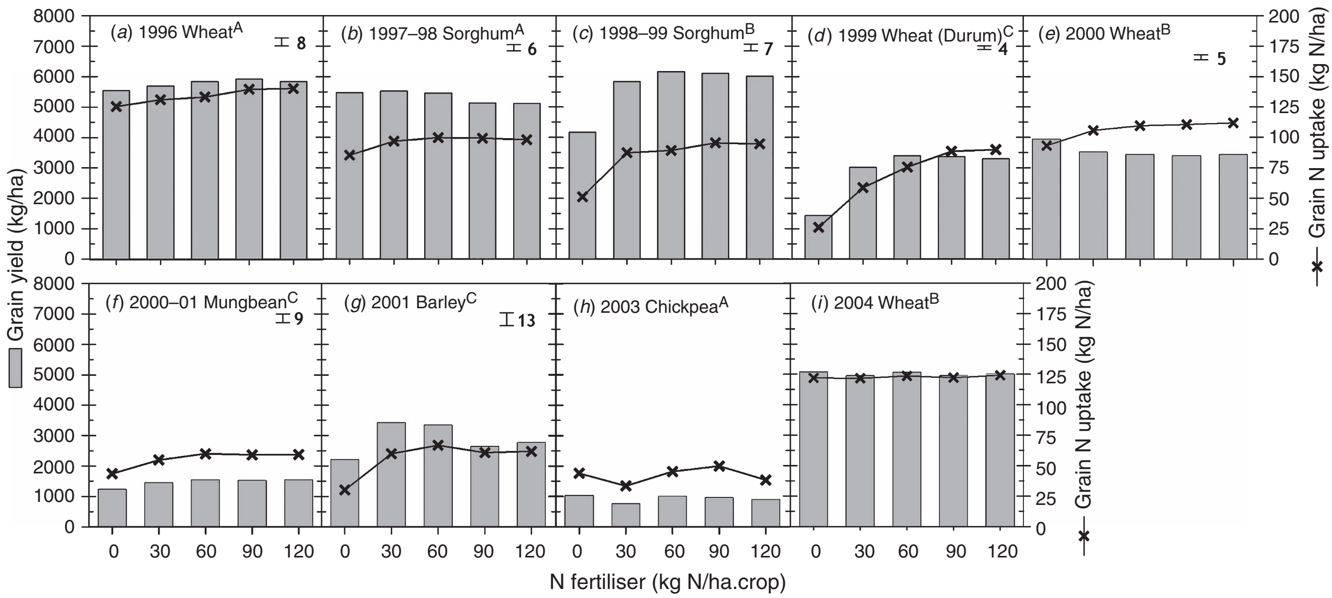

Fig. 2. Grain yield (kg/ha) and grain N uptake (kg N/ha) (×) at 5 N fertiliser treatments at Myling, Tulloona, NSW, in 1996–2004. Vertical bars are l.s.d. (P = 0.05) comparing grain N uptake with fertiliser N, blank if no significant difference (P > 0.05). [A], ~14 months fallow (long); [B], ~6 months (short); [C], <6 months (double).

Table 3. Grain N uptake (kg N/ha) of sorghum, mungbean, wheat, and chickpea crops sown after ~14 months (long), ~6 months (short), or <6 months (double) fallow periods for 3 P fertiliser treatments at Myling, Tulloona, NSW, in 1996–2004

n.s., Not significant

Crop season	Fallow length	Crop	P fertiliser rate (kg P/ha.crop) 0	10	20	l.s.d.
1996	Long	Wheat	133	135	134	n.s.
1997–98	Long	Sorghum	90	100	97	4
1998–99	Short	Sorghum	83	82	86	n.s.
1999	Double	Wheat	66	68	69	n.s.
2000	Short	Wheat	103	108	108	4
2000–01	Double	Mungbean	49	59	59	7
2001	Double	Barley	54	54	61	n.s.
2003	Long	Chickpea	38	44	45	n.s.
2004	Short	Wheat	115	127	127	5

fertiliser N at 30–60 kg N/ha (Fig. 2*c*, *d*, *g*). Generally, as yield increases or plateaus, grain N follows a similar trend (Figs 1, 2), consistent with responses in wheat (Strong *et al.* 1996*b*).

Grain N uptake in plots where no fertiliser N is applied represents background N supply comprising the sum of N mineralisation of soil organic matter and returned crop residues, plus N gained through atmospheric deposition and free-living N fixation. Duration of cultivation influenced the comparative grain N uptakes under these nil-fertiliser N treatments per crop, and cumulatively at the Colonsay and Myling sites. At Myling the grain N uptakes in the nil N treatments of 4 crops following long fallows and/or summer mineralisation periods were 124 kg N/ha (1996 wheat), 83 kg N/ha (1997 sorghum), 93 kg N/ha (2000 wheat), and 122 kg N/ha (2004 wheat), a mean of 105 kg grain N/ha. At Colonsay for the same long-fallow periods, mean grain N was 67 kg/ha. After 9 crops at Myling (1996–2004), around 630–650 kg N/ha (Table 4) in grain had been taken up, while in 17 crops at Colonsay (1985–2003), 740–760 kg N/ha grain N uptake occurred (Table 2). These results are consistent with several other north-eastern Australian studies (Dalal and Mayer 1987; Dalal 1989; Strong 1990) supporting higher mineralisable N supply capacity of soils during the early years of conversion into cultivated agriculture.

Table 4. Cumulative grain yield and grain N uptake, delta grain N, and recovery efficiency of fertiliser N in grain from plots with or without P application receiving differing amounts of N fertiliser application at the Myling experiment from 9 crops grown in 1996–2004

N fert. rate (kg N/ha.crop)	∑ N fert. applied (kg N/ha)	Nil P ∑ Grain yield	∑ Grain N	Δ Grain N	RE_{NG}	Plus P ∑ Grain yield	∑ Grain N	Δ Grain N	RE_{NG}
0	0	29 380	650			30 320	630		
30	270	31 460	730	80	0.30	34 730	770	140	0.52
60	540	33 280	760	110	0.20	35 530	830	200	0.37
90	810	32 260	770	120	0.15	34 030	840	210	0.26
120	1080	32 320	760	110	0.10	33 640	840	210	0.19

Grain N uptake of nil-N treatments under higher intensity cropping phases declined as the number of successive crops increased. This decline is supported by Strong *et al.* (1996*b*) from the Warra long-term experiment on a fertility-depleted Vertosol where grain N uptake in successive wheat crops grown from 1987 to 1990, and from 1992 to 1994, consistently declined during both cropping periods. Strong *et al.* (1996*b*) reported lower grain N uptake of unfertilised wheat after short fallows (28–53 kg N/ha) than following long fallows (69–83 kg N/ha), and the winter cereal crops at Colonsay support this distinction.

Recovery efficiency of fertiliser N in grain cumulatively and in comparison with annual winter and summer crop studies

Recently, several reviews on management practices, effects, and use implications of fertiliser N in the environment have been published (Strong 1995; Mosier *et al.* 2004; Fageria and Baligar 2005; Ladha *et al.* 2005). Ladha *et al.* (2005), in reviewing worldwide fertiliser N use efficiency in cereal production, outlines global averages of RE_{NG} for maize and wheat of 0.45 ($n = 44$) and 0.34 ($n = 368$), respectively, with an Australian mean RE_{NG} of 0.30 ($n = 74$). This may be a generalisation due to different production systems across northern and southern Australian climates (Williams *et al.* 2002). North-eastern Australia's subtropical production system has a different range of opportunities to minimise weed, disease, and pest constraints through rotation of summer and winter crops in an integrated farming system (Wylie 1997), whereas southern and western Australian cereal production systems operate within a Mediterranean climate (Williams *et al.* 2002). Use of *Brassica* break crops (primarily canola, *Brassica napus*) in southern Australia since the early 1990s has reduced disease constraints from several diseases (primarily *Gaeumannomyces* or *Rhizoctonia*), resulting in yield increases with following wheat crops (Angus *et al.* 1991; Kirkegaard *et al.* 1994); consequently, also increasing fertiliser N demand by wheat and canola crops (Angus 2001) and potentially N-use efficiency.

Without ^{15}N technology, determination of seasonal or per-crop fertiliser RE_{NG} at the Colonsay and Myling long-term sites is difficult, particularly with carryover of residual N at higher N application rates, as observed by Strong *et al.* (1996*a*) on the Darling Downs, Qld. However, calculating fertiliser RE_{NG} on cumulative fertiliser input and grain N uptakes determines long-term fertiliser N recovery efficiency within the current experimental framework. At both sites, RE_{NG} generally declined with increasing cumulative N fertiliser input, and P fertiliser treatment increased grain yield, N uptake, and RE_{NG} compared with no P application. Dalal and Probert (1997) reported N and P as the nutrients most limiting crop production within Australia's northern grains region, and grain yield (Lester *et al.* 2008) and grain N responses at Colonsay and Myling concur. The additive responses of P fertiliser to increasing N supply are consistent with other reviews (Tandon and Kanwar 1984; Aulakh and Malhi 2005). At Colonsay the RE_{NG} at the 700 kg cumulative fertiliser N/ha rate was the same with or without P application at 0.50 (Table 2). As cumulative fertiliser N input increased further, application of P fertiliser increased grain yield, N uptake, and RE_{NG} compared with nil P. The improvement in RE_{NG} with P was 0.05–0.13 across a range of cumulative N rates. Similarly, at Myling, fertiliser P input increased RE_{NG} compared with no P input, although the grain yield and N uptake increases with cumulative fertiliser N application were smaller than at Colonsay. Within the northern grains region, research into yield responses with N and P fertilisers for winter cereal crops has been extensive (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; Strong 1998; Moody and Bolland 1999). Grain yield responses to N and/or P fertilisers are associated with increases in above-ground biomass and N uptake (Hibberd *et al.* 1991; Dalal *et al.* 1995; Kamoshita *et al.* 1998; Norrish 2003) and it is this response of biomass and N uptake that is likely to be improving RE_{NG}.

The cumulative RE_{NG} at Colonsay and Myling is consistent with other seasonal fertiliser N studies in winter and summer cereals. Strong *et al.* (1996*a*) reported N recovery in the wheat grain of 0.39–0.49 in the year of application, and cumulative recovery by the 4 successive crops of N applied in the first year was 0.56 in the grain with ^{15}N. Strong *et al.* (1992) found the recovery of ^{15}N by wheat at two sites was not affected by fertiliser management practice, application depth, or use of a nitrification inhibitor. Thomas *et al.* (2007), over 5 crops and varying fertiliser N rates each year, based on measured soil water and nitrate levels, had a cumulative RE_{NG} of 0.46 at the lowest fertiliser N treatment to 0.37 at the highest. These support many single-year fertiliser N experiments with wheat, reporting RE_{NG} of 0.33–0.57 for highly responsive sites and 0.22–0.30 for sites with smaller yield increases (Doyle and Leckie 1992; Doyle and Holford 1993).

For summer cereals, sorghum appears to have the potential to recover applied fertiliser N effectively under a range of conditions. Holford *et al.* (1997) found that effects on RE_{NG} were associated with cultivation age (mineralisable N supply) across the north-west slopes and plains of NSW. In the northern area of their study, Holford *et al.* (1997) suggested that higher soil nitrate levels provided an explanation for the general lack of fertiliser N response during the study period (RE_{NG} <0.20 for all N rates), while through the southern portion under longer cultivation durations, RE_{NG} was 0.45–0.50 for 3 of the 4 years in the study. Armstrong *et al.* (1996), in a 2-year study in central Queensland, reported declining fertiliser N uptake (in grain plus straw) of 0.61 at 25 kg N/ha to 0.45 at 100 kg N/ha. These values are consistent with fertiliser N studies in grain sorghum conducted in the USA (Varvel and Peterson 1991) and India (Tandon and Kanwar 1984). Kamoshita *et al.* (1999) outlined the genotypic variation available in grain sorghum hybrids, making them capable of a high yield potential without necessarily increasing grain N concentration.

Future research topics

The results reported in this study have focused on the seasonal crop responses in grain N uptake to varying fertiliser N and P treatments, and the cumulative yield, grain N, and recovery of fertiliser N in grain. Further fertiliser N and P research opportunities ranging from economic evaluation of use, derivation of fertiliser best-management practices under opportunity cropping, to the study of nitrogen mass balance components (N mineralisation from soil organic matter, denitrification, and the recycling of nitrogen taken up by previous crops at different N and P fertiliser treatments) may be explored using soil and plant samples and data from the Colonsay and Myling long-term experiments.

Conclusions

Duration of cultivation resulted in different fertiliser N responsiveness of both yield and grain N uptake. The shorter cultivation duration at Myling (9 years at commencement) had increases in grain N with fertiliser N input $\geq$15 kg N/ha only during high cropping intensity, low N mineralisation conditions. At Colonsay the 44 years of cultivation before the experiment commenced increased the size and frequency of responses in grain yield and N uptake to fertiliser N input, with 15 of 17 harvested crops responding. Phosphorus fertiliser generally increased grain N uptake at both sites in winter cereal crops, and occasionally in long-fallow sorghum and legumes.

Where fertiliser P was applied, cumulative recovery efficiencies of fertiliser N in grain N at both sites were increased. Cumulative RE_{NG} at Colonsay was in general agreement with ranges reported for single-year experiments within the region, and was higher than reported Australian average results. The addition of fertiliser N and P to N-depleted soils in the northern grains region can be effective in increasing grain yield and grain N uptake. In the Colonsay and Myling experiments, application of fertiliser P increased cumulative fertiliser N recovery into grain N compared with nil-P input.

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