GRDC project CSP 318
Citrate-secreting break crops to unlock the fixed-P bank in conventional and organic farming rotations
Contracted output 3

Phosphorus benefits from grain legumes in rotational cropping: A field evaluation of break-crops on the yield of following wheat crops

SUMMARY

Glasshouse studies have reported improved growth and P nutrition of cereal crops when grown in rotation with a range of organic-anion secreting grain legumes such as white lupin. Field experiments that aimed at verifying and quantifying carry-over P benefits from these grain legumes to the yield of following wheat crops were conducted in 2001-2002, and 2004-2005 at 4 sites in the cropping zone of the central and southern Western Slopes of NSW. A range of organic-acid exuding and non-exuding grain legumes were grown for the break-crop phase in the first year, followed by wheat in the next season.

The results of the field experiments showed no significant carry-over P benefits of organic-acid exuding crops such as white lupin. Several factors including delayed sowing due to late seasonal breaks, drought, lack of subsoil moisture, and early finishes to most seasons combined to severely compromise both attempts to test the P benefits of the organic-acid secreting break crops. Consequently, the P carry-over benefit from organic-acid exuding legumes to a following wheat crop seen in the glasshouse still remains to be verified under ‘average’ seasonal conditions. Given that two consecutive seasons are required to verify the concept, it is recommended that any future work be done under irrigation to avoid the problems of late sowing, drought or erratic rainfall, and early finishes to the season.

INTRODUCTION

Phosphorus (P) is a major limiting factor for crop production on many Australian soils as a result of high P fixation and/or low levels of total and plant-available soil P. The application of fertiliser P is a straightforward but increasingly costly option to overcome P deficiency. Most crop species have a low use-efficiency of P fertiliser, as a significant proportion of the fertiliser P becomes ‘fixed’ in the soil and largely unavailable for plant uptake. In addition, world reserves of high quality phosphate rock are finite, and expected to be exhausted by the end of this century at current rates of usage. A major challenge therefore is to find ways to improve the overall P use-efficiency of cropping systems. Agronomic measures that have shown promising beneficial effects on P availability are the application of crop residues or other organic matter sources, and the incorporation of P-mobilising crop species and/or cultivars into the cropping system (Horst et al., 2001).

Some grain legume crops possess the capacity to mobilize soil and fertilizer P through the exudation of organic-acid anions from their roots into the rhizosphere: e.g., pigeon pea, *Cajanus cajan* (Ae et al., 1990; Otani et al., 1996), chickpea, *Cicer arietinum* (Ohwaki and Sugahara, 1993, 1997), and especially white (or Albus) lupin, *Lupinus albus* (Gardner et al., 1983; Hocking and Randall, 2001; Hens and Hocking, 2004). For example, in response to low P supply, white lupin develops cluster roots (proteoid roots) (Gardner et al., 1983; Keerthisinghe et al., 1998) that are major sites of H^+ and citrate exudation (Marschner et al., 1986; Keerthisinghe et al., 1998; Hocking, 2001; Hocking and Jeffery, 2004). This mechanism enables white lupin to acquire P from a pool of soil and/or fertiliser P that is unavailable, or at least not readidly available, to non-secreting crops such as wheat (Braum and Helmke, 1995; Hocking and Randall, 2001).

Several glasshouse studies have reported improved growth and P nutrition of less P-efficient crops when intercropped and/or grown in rotation with a range of organic-anion secreting grain legumes, indicating that the latter are able to mobilize P in excess of their own requirements (Gardner and Boundy, 1983; Horst and Waschkies, 1987; Kamh et al., 1999, 2002; Horst et al., 2001; Hocking and Randall, 2001; Hens and Hocking, 2004). However, despite the promising results from the glasshouse research, there has been negligible evaluation of the rotation benefits of organic-anion secreting grain legumes under field conditions. Ae et al. (1990) reported some evidence of improved growth of sorghum following pigeon pea, and Horst and Waschkies (1987) claimed improved growth of wheat following white lupin in field plots, but showed no supporting data.

The overall objective of GRDC project CSP 318 "Citrate-secreting break crops to unlock the fixed-P bank in conventional and organic farming rotations" is to improve P use-efficiency through legume–wheat rotations. It was hoped that the results from this project would enable grain growers to improve the use-efficiency of P from recently applied P fertiliser or organic amendments, as well as to withdraw some P from the large 'bank' of fixed soil P through the inclusion of an organic-acid secreting break crop in their rotations.

This report summarizes the results from field experiments that aimed at quantifying any carry-over P benefits from organic-acid secreting grain legumes to the yield of following wheat crops. The work was conducted in 2001-2002, and 2004-2005 at 4 sites in the cropping zone of the central and southern Western Slopes of NSW. The field experiments were largely based on the results from glasshouse experiments described in Contracted Output 1. In the work reported here, a range of organic-acid exuding and non-exuding grain legumes were grown for the break-crop phase in the first year of the field trials, followed by wheat in the next season.

METHODOLOGY

Site description

The sites for the field trials in 2001-2002 were on farmer's properties at Berthong and Greenethorpe. In 2004-2005, the sites were at Boorowa and Ooma (between Grenfell and Forbes). The previous crop at all sites was wheat. Selected site and soil parameters are shown in Table 1.

Table 1. Selected site and soil parameters. Values for soil sampled from transects accross sites at the start of 2001 and 2004 seasons

Parameter	Berthong	Greenethorpe	Boorowa	Ooma
	2001-2002		2004-2005	
Soil type	Red Kandosol	Red Kandosol	Red Chromosol	Red Kandosol
Land use	Rotation cropping	Rotation cropping	Rotation cropping	Rotation cropping
pH (0.01 M $CaCl_2$)	5.9	5.5	4.6	4.8
Total C (g/kg)	23	20	17	20
Total N (g/kg)	1.9	1.7	1.6	1.7
Total P (mg/kg)	602	332	355	305
Organic P (mg/kg)	209	78	91	110
Resin-P (mg/kg)	21.5	15.0	4.0	5.6

Field work 2001-2002

Phase I – Experimental sites, design and establishment of break crops.

Two field experiments were set up in 2001 at Berthong and Greenethorpe in the medium rainfall zone of the cropping belt of NSW, and in 2002 a back-up trial was established at Ooma. The soil at Berthong is a dark red loam derived from basalt with a high iron content, and the soils at Greenethorpe and Ooma are red-brown earths derived from granite. The basic experimental layout was split-split plot design, with P fertiliser type as the main plot, P rate as the subplots and type of break-crop as the sub-sub plots (hereafter termed plots for convenience). There were 4 replicates of each treatment. Plot size was 30 x 2.2 m, with 10 rows spaced 18 cm apart. Soil total-P (0-10 cm) at the start of the season was determined for each site by taking 20 samples each from 3 transects across the top, middle and bottom of each site. Soil samples from each transect were bulked for total-P analysis. Resin-extractable P (a good estimator of plant-available P) was determined for all plots at both sites, by taking 15 cores at 2 m-intervals down each plot and bulking the samples from each plot. Soil concentrations of total P and plant-available (resin-extractable) P at the sites are shown (Table 1).

In early May, 2001, two organic-acid secreting crops (white lupin cv. Kiev Mutant and chickpea cv. Amethyst), and a non-secreting crop faba bean (*Vicia faba* cv. Fiesta), were sown at two P fertiliser rates [0P, and 25 kg P/ha either as single superphosphate (SSP)or as reactive rock phosphate (RRP)] at Berthong and Greenethorpe. There were bare soil control plots that received the same tillage treatment and P fertiliser forms and rates as the planted plots. White lupin and chickpea exude from their roots organic acids such as citrate, malonate and malate that have been shown to solubilise fixed forms of soil P. Earlier work had indicated that faba bean did not appear to exude significant levels of organic acids or other P solubilising compounds such as phosphatases in response to P-deficiency (see Output 2 Report). The same experimental design, P forms and rates, and break crops as at Berthong and Greenethorpe in 2001 were used for the back-up trial at Ooma in 2002. At all sites, the crops were sown after land preparation by the farmers for their own crops (canola). The legume seeds were inoculated with the appropriate strain of *Rhizobium* prior to sowing. Weed control was achieved using Treflan® pre-sowing, and Gesatop® and Sencor® post-sowing but pre-emergence, and by hand hoeing for broadleaf weeds and spraying with Verdict® for grass weeds during the season. Talstar® was applied pre-emergence to control red-legged earth mites (RLEM). Recommended fungicides were applied when appropriate. Plants were sampled at the start of flowering by placing 1-m^2 quadrats 2 m in from the ends of each plot, and cutting the shoots off at ground level. Seed yields were obtained by machine harvesting the inner 8 rows of a 25-m long section of each plot after trimming the ends.

Just prior to flowering, 10 white lupin plants were carefully excavated from each of the 0P, RRP and SSP plots to assess if they had produced cluster roots. Rhizosphere soil was gently shaken from the cluster roots of plants and assayed for citrate, which generally accounts for 80-90% of the total organic acids exuded from white lupin cluster roots (Keerthisinghe et al., 1988) using a modified technique based on Veneklaas et al. (2003). Organic acids were not determined for rhizosphere soil from chickpea roots as we had no means available to measure malonic acid, the dominant organic acid exuded from roots of this crop (Veneklaas et al., 2003).

Phase 2 – Establishment of wheat

In 2002, all plots at Berthong and Greenethorpe were randomly split in half for P fertiliser application (0P or 25 kg P/ha as triple superphosphate) and direct-drilled to wheat cv. H45 on 13 and 18 June, respectively. The 0P half-plots were to determine the residual value of the P applied in the previous season. A 2-m long buffer zone was left between the two 14-m long half-plots to delineate the + and – P sections. Soil samples (0-10 cm) were taken from all plots for resin-extractable P, and from 0-20 cm for mineral N analysis prior to sowing. The results for soil mineral N showed that at Greenethorpe, all plots (including the bare soil) had similar levels (mean 25.4 mg N/kg), and at Berthong all the legume plots were also similar for N (mean 37.8 mg N/kg) but the bare-soil plots were lower (26.6 mg N/kg). Consequently, all plots at both sites received 30 kg N/ha as urea at sowing except for the bare-soil ones at Berthong which received 50 kg N/ha, so that the initial amount of mineral N available to the wheat was approximately the same across all plots at a particular site. The wheat was top-dressed with an additional 30 kg N/ha as urea at DC31 (start of stem elongation with one node visible) to ensure that N did not limit growth. Weed control was achieved by a mixture of Logran® and Roundup® prior to sowing, and broadleaf weeds with a mixture of MCPA and Lontrel® prior to stem elongation.

Plants were sampled for dry-matter production at the start of anthesis by placing 0.5-m^2 quadrats 2 m in from the ends of each half-plot, and cutting the shoots off at ground level. Grain yield was obtained by machine harvesting the inner 8 rows from a 12-m long section of each half-plot.

Field work 2004-2005

Phase I – Experimental sites, design and establishment of break crops.

The two sites chosen had low levels (<10 mg/kg) of resin-extractable P but reasonable levels of total P (300-350 mg/kg) (Table 1). The first site was again at Ooma and the other site was at Boorowa, in the medium and higher rainfall zones of the cropping belt, respectively. Although the site at Ooma received good rainfall in early 2004 from summer/autumn storms, sowing of the break crops was delayed until mid-May because plague locusts invaded the region. Sowing at Boorowa was delayed until the first week of June because of a very late break to the season.

The break crops at both sites were white lupin (cv. Kiev Mutant), narrow-leaf lupin (*Lupinus angustifolius* cv. Quilinock at Ooma and cv. Jindalee at Boorowa, chickpea cv. Howzat, and faba bean cv. Fiesta. Narrow-leaf lupin was included as a supplementary control to faba bean as it does not exude significant quantities of organic acids under conditions of P deficiency (Hocking and Jeffery, 2004). Also, the results of short-term glasshouse experiments reported in Output 2 and elsewhere (Nuruzzaman et al. 2004) indicated that faba bean may have a beneficial effect on the P nutrition and growth of a following crop. The legumes were grown at the same rates of P fertiliser as in 2001 (0P or 25 kg P/ha applied as either SSP or RRP), and the bare soil controls received the same tillage and P treatments as the legume crops. Plot size was the same as in 2001, and there were 4 replicates of each treatment randomised within 4 blocks. The crops at Ooma were direct-drilled into wheat stubble, but at Boorowa, the plots were cultivated to 20 cm with non-inversion chisel tines and harrowed to provide an even seedbed. All legumes were inoculated prior to sowing. Weed and RLEM control was the same as in 2001, as were the prophylactic fungicide sprays.

Soil was sampled for total soil P (0-10 cm) using the transect method as in 2001. Resin-extractable soil P was determined at both sites from each plot at the start of the season, flowering, and maturity of the crops. The crops were sampled at flowering for dry-matter production (quadrat cuts) and machine harvested for seed yield.

Phase 2 – Establishment of wheat

In 2005, each plot was split in half as in 2002 and direct-drilled to wheat cv. Sunvale at 2 rates of P fertiliser (0 and 25 kg P/ha as SSP). The wheat was sown on June 17 at Ooma, and on July 5 at Boorowa. However, at Boorowa, severe surface crusting of the soil following very heavy rainfall during a storm and then dry windy conditions, plus damage to recently-emerged seedlings by sulphur-crested cockatoos, resulted in such a low and patchy plant establishment that the plots were sprayed out and re-sown into the previous rows on August 18.

Resin-extractable P (0-10 cm) and mineral N (0-20 cm) were determined for all plots at the sites just prior to sowing. There were only small differences in the mineral N status of the legume plots at both sites, so 10 kg N/ha (as urea) was applied to these plots and 30 kg N/ha to the bare-soil plots to ensure that N levels were similar across all plots. An extra 30 kg N/ha as urea was topdressed at both sites at DC31. Weed control was the same as in 2002. The wheat was sampled for dry matter at DC31 at Ooma, and at anthesis at both sites using quadrats as in 2002. Some of the anthesis samples from Ooma were destroyed by a fire in the dehydrator, so the results from the harvest at DC31 are presented for that site. The plots were machine harvested for grain yield on 21 December at Ooma, and 16 January 2006 at Boorowa.

Statistical analysis

The effects of prior crop and P fertiliser were tested using ANOVA (GenStat 6). Differences between means were tested for statistical significance using LSD values at P = 0.05.

RESULTS

2001-2002 seasons

Phase I – Growth and yield of break crops, 2001

Growth of the break crops at both sites in 2001 was good by district standards, particularly at Berthong. Dry-matter production of chickpea and faba bean at the start of flowering only responded to SSP at Berthong, whereas white lupin did not respond to P fertiliser, and at Greenethorpe, only chickpea responded to SSP (Table 2).

Table 2. Dry matter (t/ha) of break crops at start of flowering at Berthong and Greenethorpe, 2001

Break crop	P fertiliser applied (kg/ha)					
	0	25 RRP	25 SSP	0	25 RRP	25 SSP
	Berthong			Greenethorpe		
Chickpea	1.44a	1.46a	1.83b	1.25a	1.20a	1.71b
Faba bean	2.85a	3.11a	3.50b	2.00a	2.40a	2.40a
White lupin	2.84a	2.70a	3.20a	3.26a	3.05a	3.38a

Values in a row for the same site with the same letter do not differ significantly

However, by maturity, seed yields for each crop did not differ between P treatments at a given site (Table 3). Dry-matter production and seed yields at Berthong were generally higher than at Greenethorpe (Tables 2 and 3).

Table 3. Seed yields (t/ha) of break crops at Berthong and Greenethorpe, 2001

Break crop	P fertiliser applied (kg/ha)					
	0	25 RRP	25 SSP	0	25 RRP	25 SSP
	Berthong			Greenethorpe		
Chickpea	3.24a	3.04a	3.40a	1.31a	1.57a	1.58a
Faba bean	4.83a	5.07a	4.95a	3.17a	3.13a	3.34a
White lupin	3.34a	3.47a	3.63a	3.23a	3.15a	3.13a

Values in a row for the same site with the same letter do not differ significantly

Phase 2 – Growth and yield of wheat, 2002

The break-crop effect was analysed for each site separately, as the effect of site was greater than any break-crop effect (Table 4). Wheat dry-matter production at Berthong was higher than that at Greenethorpe, reflecting the generally better growing conditions at Berthong. There was a significant residual effect of the SSP from 2001, but there was no residual benefit from the RRP. The application of 25 kg P/ha as TSP significantly increased growth at both sites, irrespective of the prior crop and the residual effect of the SSP.

The break-crop benefit to the growth of the following wheat was negligible (Greenethorpe) and/or inconsistent (Berthong) when compared with the bare soil controls (Table 4). This was largely attributed to the greater water use by the break crops compared to the bare soil (fallow) controls, thus reducing soil water availability, particularly at depth, to the wheat during the drought of the 2002 season.

Table 4. Wheat dry matter (t/ha) at anthesis at Berthong and Greenethorpe, 2002

Site	Berthong						Greenethorpe					
P rate and form												
2001	0		25RRP		25SSP		0		25RRP		25SSP	
2002	0	25TSP	0	25TSP	0	25TSP	0	25TSP	0	25TSP	0	25TSP
Break crop in 2001												
BS	2.11a	3.73b	2.27a	3.97bc	3.26b	4.02c	1.08a	1.50b	1.00a	1.68bc	1.55b	1.82c
CP	2.52a	3.29b	2.33a	3.45b	2.93ab	3.49b	0.76a	1.37b	0.76a	1.42b	1.34b	1.74c
FB	2.33a	3.95c	2.34a	3.59bc	3.11b	3.77c	0.80a	1.35b	0.94a	1.37b	1.38b	1.74c
WL	1.80a	3.36b	2.01a	3.62c	2.83b	3.47c	0.74a	1.30b	0.91ab	1.32b	1.20b	1.68c
l.s.d. (*P*=0.05)	0.33	0.41	ns	0.49	ns	0.44	0.30	ns	ns	0.31	0.33	ns

Values in a row at the same site with the same letter do not differ significantly. Abbreviations for break crops: BS, bare soil; CP, chickpea; FB, faba bean; WL, white lupin.

Some of the differences in dry-matter production at anthesis due to P fertiliser did not translate into grain yield at maturity, because of haying-off as a consequence of the drought, particularly at Berthong (Table 5). At Berthong, the likely saving in soil water use by the wheat crops with lower biomass at anthesis enabled them to catch up with the higher-biomass plots with respect to grain yield. This effect was more apparent at Berthong where there was the potential for higher yielding crops than at Greenethorpe.

Table 5. Wheat grain yields (t/ha) at Berthong and Greenethorpe, 2002

Site	Berthong						Greenethorpe					
P rate and form												
2001	0		25RRP		25SSP		0		25RRP		25SSP	
2002	0	25TSP	0	25TSP	0	25TSP	0	25TSP	0	25TSP	0	25TSP
Break crop in 2001												
BS	3.10a	2.95a	3.05a	3.50b	3.15a	3.58b	1.73a	2.02a	1.82a	2.21ab	2.38b	2.14ab
CP	2.84a	2.92a	3.01a	2.92a	3.08a	2.87a	1.72a	2.10b	1.71a	2.19b	2.08b	2.19b
FB	3.24a	3.26a	3.43a	3.24a	3.23a	3.68b	1.90a	2.13ab	1.80a	2.17b	1.99a	2.05a
WL	2.77a	3.25b	2.92a	3.16b	2.82a	3.04ab	1.50a	2.18b	1.69a	2.12b	1.89ab	2.13b
l.s.d. (*P*=0.05)	0.32	ns	0.38	0.51	ns	0.49	0.24	ns	ns	ns	0.38	ns

Values in a row at the same site with the same letter do not differ significantly. Abbreviations for break crops: BS, bare soil; CP, chickpea; FB, faba bean; WL, white lupin.

There was no residual effect of the prior P fertiliser application on grain yields at Berthong, but a small residual effect of SSP on the bare soil and chickpea plots at Greenethorpe. The application of TSP to the wheat at Berthong had inconsistent effects on grain yield, but a greater effect at Greenethorpe, although again, it was not consistent. The ANOVA showed that there was no overall significant effect of break crop at either site. Wheat yields following Faba bean were no different from those following the organic-acid secreting crops, chickpea and white lupin (Table 5).

2004-2005 seasons

Phase I – Growth and yield of break crops, 2004

Dry-matter production at flowering was increased by RRP and SSP for all crops at Boorowa, except for white lupin which showed no response (Table 6). RRP was as effective as SSP in increasing dry matter. At Ooma, the dry matter of chickpea and faba bean was increased by RRP and SSP, but only by SSP for narrow-leaf lupin. Chickpea and faba bean showed a greater response to SSP than RRP at Ooma, but not Boorowa. There was no significant growth response to P fertiliser by white lupin (Table 6).

Table 6. Dry matter (t/ha) of break crops at flowering at Boorowa and Ooma, 2004

Break crop	P fertiliser applied (kg/ha)					
	0	25 RRP	25 SSP	0	25 RRP	25 SSP
	Boorowa			Ooma		
Chickpea	1.46a	2.76b	2.38b	1.02a	2.35b	3.33c
Faba bean	3.01a	4.80b	4.45b	2.55a	4.19b	4.95c
Narrow-leaf lupin	2.29a	3.97b	4.12b	3.25a	3.37a	4.70b
White lupin	1.34a	1.66a	1.69a	3.79a	3.97a	3.88a

Values in a row for the same site with the same letter do not differ significantly

Seed yields of chickpea and faba bean increased in response to P fertiliser at both sites, but SSP was superior to RRP only for faba bean at Ooma (Table 7). The seed yield of narrow-leaf lupin was increased to the same extent by both RRP and SSP at Boorowa, but this species showed no response to P fertiliser at Ooma. White lupin did not respond to P fertiliser at either site. The yields of chickpea and particularly white lupin were generally higher at Ooma than at Boorowa (Table 7), probably as a result of the later sowing at Boorowa and a rapid finish to the season.

Table 7. Seed yields (t/ha) of break crops at Boorowa and Ooma, 2004

Break crop	P fertiliser applied (kg/ha)					
	0	25 RRP	25 SSP	0	25 RRP	25 SSP
	Boorowa			Ooma		
Chickpea	1.14a	1.46b	1.52b	1.39a	2.01b	2.04b
Faba bean	1.30a	1.73b	1.99b	1.27a	1.73b	2.32c
Narrow-leaf lupin	1.31a	1.96b	2.00b	2.01a	2.15a	2.10a
White lupin	0.93a	0.99a	1.09a	1.92a	1.93a	1.98a

Values in a row for the same site with the same letter do not differ significantly

Phase 2 – Growth and yield of wheat, 2005

There was no significant residual effect of the previous fertiliser (2004) on the dry-matter production of wheat at either Boorowa or Ooma, except for the bare-soil treatment at Ooma (Table 8). The application of TSP in 2005 increased dry matter at Boorowa for the 2004 SSP treatments that had a prior crop, but increased the dry matter of most wheat crops at Ooma. There were some inconsistent break-crop effects on the growth of wheat at both sites (Table 8), but ANOVA showed no overall break-crop effect at either site.

Table 8. Wheat dry matter (t/ha) at anthesis at Boorowa and at DC 31 at Ooma, 2004

Site	Boorowa (anthesis)						Ooma (DC 31)					
P rate and form												
2004	0		25RRP		25SSP		0		25RRP		25SSP	
2005	0	25TSP	0	25TSP	0	25TSP	0	25TSP	0	25TSP	0	25TSP
Break crop in 2004												
BS	2.72a	3.26b	3.12ab	3.15ab	2.77a	2.98a	0.53a	1.31c	0.82b	1.17bc	0.88b	1.37c
CP	2.57a	2.76a	2.76a	2.87a	2.93ab	3.17b	0.88a	1.43c	0.82a	1.35c	1.04ab	1.19b
FB	2.71a	3.12ab	2.63a	2.67a	2.76a	3.40b	0.73a	1.02b	0.62a	0.98b	0.75a	0.94b
NL	2.95a	3.04a	2.89a	3.14a	2.73a	3.30b	0.69a	1.30b	0.75a	1.20b	0.85a	1.55c
WL	2.50a	3.42b	2.50a	3.17b	2.52a	3.23b	0.82a	1.06a	1.03a	1.15ab	0.87a	1.34b
l.s.d. (*P*=0.05)	ns	0.33	0.29	0.38	ns	ns	0.20	0.26	0.23	0.27	0.29	0.33

Values in a row at the same site with the same letter do not differ significantly. Abbreviations for break crops: BS, bare soil; CP, chickpea; FB, faba bean; NL, narrow-leaf lupin; WL, white lupin.

Table 9. Wheat grain yields (t/ha) at Boorowa and Ooma, 2005

Site	Boorowa						Ooma					
P rate and form												
2004	0		25RRP		25SSP		0		25RRP		25SSP	
2005	0	25TSP	0	25TSP	0	25TSP	0	25TSP	0	25TSP	0	25TSP
Break crop in 2004												
BS	2.19a	2.66b	2.58b	2.64b	2.11a	2.86b	3.92a	4.57b	4.21ab	4.51b	3.96a	4.48b
CP	1.97a	2.28a	2.15a	2.69b	2.19a	2.49b	3.59a	4.21b	3.93a	4.26b	4.11b	4.20b
FB	2.07a	2.29a	1.87a	2.42b	2.03a	2.52b	3.22a	3.84b	3.52ab	3.88b	3.70b	3.96b
NL	1.97a	2.12a	2.02a	2.57b	2.11a	2.52b	3.84a	4.06a	3.84a	4.26b	3.83a	4.31b
WL	1.85a	2.28b	2.21b	2.43b	2.00a	2.45b	3.98a	4.05a	3.99a	4.35b	3.81a	4.17ab
l.s.d. (*P*=0.05)	ns	ns	0.26	ns	ns	ns	0.39	0.36	0.40	0.43	ns	ns

Values in a row at the same site with the same letter do not differ significantly. Abbreviations for break crops: BS, bare soil; CP, chickpea; FB, faba bean; NL, narrow-leaf lupin; WL, white lupin.

Grain yields at Ooma were consistently higher than at Boorowa (Table 5). There was no residual effect of the 2004 P application at Boorowa, but at Ooma there was a residual effect on wheat yield from the SSP applied in 2004 to the chickpea and faba bean plots. At Boorowa and Ooma, the application of TSP in 2005 increased the grain yield of wheat from plots that had received either RRP or SSP in 2004. There was negligible prior crop effect at Boorowa, and inconsistent effects at Ooma (Table 9).

DISCUSSION

It is clear that the significant carry-over P benefits of organic-acid exuding crops such as white lupin that have been demonstrated in short-term glasshouse experiments were not manifested in the field experiments. However, the conditions of the glasshouse experiments must be kept in mind: these include controlled day/night temperatures and daily watering of the plants to near field capacity. In addition, the following cereal crops were usually sown 6-8 weeks after the break-crop phase (e.g. Hocking and Randall, 2001; Hens and Hocking, 2004; Nuruzzaman et al., 2005), likely enabling a maximum break-crop effect to be obtained.

The field experiments reported here suffered from a number of problems beyond control, including very late breaks to the season, drought, erratic rainfall and dry finishes, all of which would have compromised the results. Unlike nitrogen, P is extremely immobile in soils, and plant root systems need to actively grow through the soil to maintain uptake of the nutrient. In addition, over 90% of the P in most cropping soils is confined to the top 5-10 cm of the soil profile. Consequently, when the surface soil dries out, root uptake of P from the 5-10 cm zone is dramatically reduced, and plant growth is constrained because of an inadequate supply of P, even though there may be good subsoil moisture. Low soil temperatures, as a consequence of late sowing, also reduce root and shoot growth, and thus P uptake. In addition, the long period between harvesting the break crop and sowing the wheat due to late breaks to the season may well have minimised any P benefit from the break crop due to P released from the crop root residues being fixed to soil minerals, or being sequestered by soil micro-organisms. Collectively, these factors are likely to have confounded any carry-over P benefit from the break crop.

Inspection of the root systems of white lupins from all the P treatments at both sites just before the start of flowering in 2001 showed that they had produced cluster roots. Rhizosphere soil citrate concentrations averaged for both sites were 210±66 μmol/g cluster-root dry weight for the 0P plots, 160±43 μmol/g for the 25RRP plots, and 90±26 μmol/g for the 25SSP plots. Presumably, the lower level of citrate in the rhizosphere soil of the 25SSP plots was a consequence of their higher levels of plant-available P. It has shown that although white lupin produces similar numbers of cluster roots at quite high levels of available P as at low available-P levels, the exudation of citrate from the cluster roots declines with increasing P availability (Keerthisinghe et al., 1988). Analysis of soil samples from the white lupin plots prior to sowing the wheat in 2002 did not show the presence of any citrate, indicating its degradation by soil micro-organisms.

A further complicating factor at all sites was an unexpected increase in resin-extractable P in all plots, including the treatments that received no P. An example of this is shown in Table 10 for the P treatments at Boorowa in 2004 averaged for each of the break crops (including the bare-soil treatment) just before sowing and at harvest of the break crops. A further example is shown in Table 11 for the P treatments between the start of the season and flowering of the break crops at Ooma in 2004 averaged for each P treatment for all the break crops. The reason for this increase in plant-available P is not clear, especially in the P0 treatment, but could be related to both mineralisation of soil organic matter and drought/rainfall effects on the soil microbial population, especially lyseing, which would release inorganic P, and provide a source of labile organic P for mineralisation.

Table 10. Resin-extractable P (mg/kg air-dried soil) at the start and end of the 2004 season at Boorowa. Values are means for soil samples from each replicate plot

Break crop	P fertiliser applied (kg/ha)		
	0	25 RRP	25 SSP
Start of season	8.8a	8.9a	9.3a
End of season			
Bare soil	23.5a	21.0a	23.5a
Chick pea	16.8a	17.8a	20.4b
Faba bean	17.5a	18.0a	15.6a
Narrow-leaf lupin	15.8a	18.2ab	19.1b
White lupin	20.5b	15.4a	23.6b
l.s.d. (*P*=0.05)	4.6	5.2	4.9

Values in a row with the same letter do not differ significantly. Values for the start of the season were obtained before P fertiliser application.

Table 11. Resin-extractable P (mg/kg air-dried soil) at the start of the season and at flowering of the break crops in 2004 at Ooma. Values are means for soil samples from all plots that received the same P treatment

P treatment	Resin-extractable P	
	Start of season	Flowering
0P	7.80a	14.28b
25RRP	8.89a	15.71b
25SSP	9.28a	16.03b

Values in a row with the same letter do not differ significantly.

The lack of any significant response to P fertiliser by white lupin at all sites confirms previous work that this species can access sources of soil P not available to crops that do not secrete significant quantities of organic acids from their roots (e.g., Braum and Helmke, 1995; Hocking and Randall, 2001). It is common practice for farmers to apply 20-25 kg P/ha to white lupin crops, but the results from this study indicate that this rate may well be too high. Assuming a yield in an 'average' season yield of 3 t/ha and a P concentration in seeds of 3.5 g/kg, then removal of P in the seeds amounts to 10.5 kg/ha. Given that white lupin can access fixed sources of soil P, and that most cropping soils have a P 'bank' of 350-500 kg/ha, most of which has been derived from previous P fertiliser applications, then fertiliser rates could be reduced to around 10 kg P/ha for this crop without 'mining' the soil.

2001/02 seasons

Although the growth of the break crops was good in 2001, and set up the prospect of field evaluation of the results obtained in glasshouse experiments, the severe drought during the 2002 season compromised the experiment to such an extent that meaningful conclusions could not be drawn from the results. The farmers on whose properties the trials were conducted at Berthong and Greenethorpe had well-below anticipated yields from their wheat crops, and the farmer at Greenethorpe cut some of his wheat for hay. In addition, the 2002 back-up site at Ooma was abandoned because growth of all the legumes was so poor.

2004/05 seasons

The delayed sowings in 2004 and a period of extremely hot, dry windy weather in October reduced growth and grain yields of the break crops. While it was not unexpected that white lupin did not respond to the applied P, it was surprising that narrow-leaf lupin did not respond to P fertiliser at Ooma, although it did respond to RRP and SSP at Boorowa. Narrow-leaf lupin has an ability to acidify its rhizosphere, probably by H^+ extrusion as a consequence of excess cation uptake (Jarvis and Robson, 1983; Coventry and Slattery, 1991; McLay et al., 1997). It is possible the acidification of the rhizosphere brought about the dissolution of the RRP (which is essentially calcium phosphate), thus releasing orthophosphate for uptake by the plant. Overall, Faba bean showed the greatest response to applied P, indicating that this species has no special adaptation to access poorly-available forms of soil P (see also Output 2). Although seasonal rainfall in 2005 was close to the long-term average for Boorowa and Ooma, the very late start to the season, and the necessity to re-sow the wheat at Boorowa due to soil-surface crusting and bird damage, resulted in lower yields than expected, and again compromised the field trials.

CONCLUDING COMMENTS

Several factors including delayed sowing due to late seasonal breaks, drought, lack of subsoil moisture, and early finishes to most seasons combined to severely compromise both attempts to test the P benefits of organic-acid secreting break crops under field conditions. After a good season in 2001 that resulted in excellent legume crops at Berthong and Greenethorpe, the late start to the 2002 season delayed sowing of the wheat, and drought resulted in poor growth and yields that compromised any response to the prior crop and P fertiliser. Late sowing of the legumes in 2004 due to locusts at Ooma and a very late break to the season at Boorowa, combined with an early finish to the season resulted in poor growth and yields. Similarly, the very late break to the 2005 season delayed sowing of the wheat, and at Boorowa it had to be re-sown in August, which drastically reduced its yield potential and thus ability to show a response to any carry-over P benefit from the prior crops.

Collectively, the results indicate that the organic-acid secreting legumes offer no significant P benefit to a following wheat crop if sowing of the break crops and the wheat is substantially delayed, subsoil moisture is lacking, and drought prevails. For a fair evaluation, the work needs to be done over 2 ‘average’ seasons when sowings can be made at the recommended time, subsoil moisture is adequate, and at least ‘average’ rainfall occurs throughout the growing season. Consequently, the P carry-over benefit from organic-acid exuding legumes to a following wheat crop seen in the glasshouse work remains to be verified under reasonable field conditions. Given that two consecutive seasons are required to verify the concept, it is recommended that any future work be done under irrigation to avoid the problems of late sowing, drought or erratic rainfall, and early finishes to the season.

However, even if organic-acid secreting crops are shown to have a beneficial P effect to a following wheat crop, a benefit/cost analysis needs to be undertaken, taking into account a number of possible scenarios. For example, given the likely significant increase in the production of bio-diesel using oilseed crops such as canola and sunflower, then there will be a large amount of good-quality meal flowing into the feed-lot market, which could undermine the price of traditional feed-lot legumes such as lupins, thus negating the value of any P benefits. In addition, grain legumes such as white lupin and chickpea require better disease resistance to reduce the number of costly fungicidal sprays. This is particularly important for organic farming systems where phosphorus availability is often one of the major problems limiting enterprise sustainability, and where the use of crops that free-up fixed soil P would be of great benefit. Despite these possible limitations to the use of crops that free-up fixed soil P, the fact that sources of high quality rock phosphate are finite and diminishing rapidly should provide the stimulus for further research on P-efficient crops.

REFERENCES

Ae, N., Arihara, J., Okada, K., Yoshihara, T., and Johanson, C. (1990). Phosphorus uptake by pigeonpea and its role in cropping systems of the Indian subcontinent. Science 248: 477–480.

Braum, S.M., and Helmke, P.A. (1995). White lupin utilizes soil-phosphorus that is unavailable to soybean. Plant Soil 176: 95–100.

Coventry, D.R. and Slattery, W.J. (1991). Acidification of soil associated with lupins grown in a crop rotation in north-eastern Victoria. Aust. J. Expt. Agric. 42: 391-397.

Gardner, W.K., and Boundy, K. (1983). The acquisition of phosphorus by *Lupinus albus* L. IV. The effect of interplanting wheat and white lupin on the growth and mineral composition of the two species. Plant Soil 70: 391–402.

Gardner, W.K., Barber, D.A., and Parbery, D.G. (1983). The acquisition of phosphorus by *Lupinus albus* L. III. The probable mechanism by which phosphorus movement in the soil/root interface is enhanced. Plant Soil 68: 19–32.

Hens, M. and Hocking, P.J. (2004). An evaluation of the phosphorus benefits from grain legumes in rotational cropping using ^{33}P isotopic dilution. In: 'New directions for a diverse planet'. Proc. 4th Internat. Crop Sci. Congress, Brisbane. On CD Rom.

Hocking, P.J. (2001). Organic acids exuded from roots in phosphorus uptake and aluminum tolerance of plants in acid soils. Adv. Agron. 74: 63–97.

Hocking, P.J. and Jeffery, S. (2004). Cluster-root production and organic anion exudation in a group of old-world and a new-world lupin. Plant Soil 258: 135-150.

Hocking, P.J. and Randall, P.J. (2001). Better growth and phosphorus nutrition of sorghum and wheat following organic acid secreting crops. In 'Plant nutrition. Food security and sustainability of agro-ecosystems through basic and applied research', Eds W.J. Horst *et al*. pp. 548-549. (Kluwer Academic Publishers: Dordrecht, The Netherlands).

Horst, W.J., and Waschkies, C. (1987). Phosphorus nutrition of spring wheat in mixed culture with white lupin. Z. Pflanzenernähr. Bodenk. 150: 1–8.

Horst, W.J., Kamh, M., Jibrin, J.M., and Chude, V.O. (2001). Agronomic measures for increasing P availability to crops. Plant Soil 237: 211–223.

Jarvis, S.C. and Robson, A.D. (1983). The effects of nitrogen nutrition of plants on the development of acidity in Western Australian soils. II. Effects of differences in cation/anion balance between plant species grown under non-leaching conditions. Aust. J. Agric. Res.34: 355-365.

Kamh, M., Horst, W.J., Amer, F., Mostafa, H., and Maier, P. (1999). Mobilization of soil and fertilizer phosphate by cover crops. Plant Soil 211: 19–27.

Kamh, M., Abdou, M., Chude, V., Wiesler, F., and Horst, W.J. (2002). Mobilization of phosphorus contributes to positive rotational effects of leguminous cover crops on maize grown on soils from northern Nigeria. J. Plant Nutr. Soil Sci. 165: 566–572.

Keerthisinghe, G., Hocking, P.J., Ryan, P.R., and Delhaize, E. (1988). Effect of phosphorus supply on the formation and function of proteoid roots of white lupin (*Lupinus albus* L.). Plant Cell Environ. 21: 467–478.

McLay, C.D.A., Barton, L. and Tang, C. (1997). Acidification potential of ten grain legume species grown in nutrient solution. Aust. J. Agric. Res. 48: 1025-1032.

Marschner, H., Römheld, V, Horst W.J., and Martin, P. (1986). Root induced changes in the rhizosphere: importance for the mineral nutrition of plants. Z. Pflanzenernähr. Bodenk. 149: 441–456.

Nuruzzaman, M., Lambers, H., Bolland, M.D.A. and Veneklass, E.J. (2005). Phosphorus benefits of different legume crops to subsequent wheat grown in different soils of Western Australia. Plant Soil 271:175-187.

Ohwaki, Y., and Sugahara, K. (1993). Genotypic differences in responses to iron deficiency between sensitive and resistant cultivars of chickpea (*Cicer arietinum* L). Plant Soil 156: 473–476.

Ohwaki, Y., and Sugahara, K. (1997). Active extrusion of protons and exudation of carboxylic acids in response to iron deficiency by roots of chickpea (*Cicer arietinum* L). Plant Soil 189: 49–55.

Otani, F., Ae, N., and Tanaka, H. (1996). Uptake mechanisms of crops grown in soils with low P status. II. Significance of organic acids in root exudates of pigeonpea. Soil Sci. Plant Nutr. 42: 533–560.

Veneklaus, E.J., Stevens, J., Cawthray, G.R., Turner, S., Grigg, A.M. and Lambers, H. (2003). Chickpea and white lupin rhizosphere carboxylates vary with soil properties and enhance phosphorus uptake. Plant Soil 248: 187-197.