An evaluation of the phosphorus benefits from grain legumes in rotational cropping using ^{33}P isotopic dilution

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Abstract

A glasshouse experiment was conducted to evaluate the break-crop benefits of chickpea, faba bean, white lupin, canola and wheat to the phosphorus (P) nutrition and growth of following canola plants. Three soils (Berthong, BT; Grenfell, GF; and Robertson, RB) were labelled with ^{33}P to quantify the size of the soil P pools accessed by the species using ^{33}P isotopic dilution (*L* values), and to evaluate the role of P in the break-crop effect. Growth and P uptake of canola and wheat were in the order BT>GF>RB, reflecting soil P availability. In contrast, the 3 legumes had better growth and P uptake than canola or wheat on the low-P soils (RB, GF). Overall, the *L* values showed that white lupin accessed a larger pool of soil P than faba bean, chickpea, wheat and canola. Canola growth was lowest after wheat and canola on all soils. On RB, faba bean had the greatest P break-crop effect and chickpea had no effect. On GF and BT, all the legumes increased the growth and P uptake of the following canola. The unexpected large break-crop effect of faba bean may be due to uptake by the following crop of mineralised P from faba bean root residues.

Media summary

White lupin was able to access sources of soil phosphorus unavailable to chickpea, faba bean, canola or wheat. Canola after the legumes had better growth and phosphorus nutrition than after canola or wheat.

Key Words

break crops, organic-acid anions, legumes, cropping systems

Introduction

Phosphorus (P) is a major limiting nutrient for crop production on many Australian soils due to high P fixation and low levels of plant-available soil P. Grain producers in Australia spend about $450 million annually on P fertiliser, but only 10-20 % of the applied P is utilized by crops in the year of application and subsequent usage of the residual P rarely exceeds 50% (Bolland and Gilkes 1998). Fertiliser P reacts with soil constituents and is readily ‘fixed’ as adsorbed P, sparingly soluble P-precipitates (Al-P, Fe-P or Ca-P) or converted to organic forms that are largely unavailable to most crop plants. A major challenge is to find ways to improve the P use-efficiency of cropping systems. One approach that has potential benefits on P availability is the incorporation of P-mobilising species into the cropping system (Horst et al. 2001).

Several legume crops can mobilise soil and fertiliser P through the exudation of organic-acid anions from their roots eg, chickpea (Veneklaas et al. 2003), pigeon pea (Otani et al. 1996) and white lupin (Gardner et al. 1983; Keerthisinghe et al. 1998). This mechanism enables some of these species to acquire P from soil sources that are not readily available to non-secreting crops (Hocking et al. 1997). A number of studies have reported improved growth and P nutrition of less P-efficient crops following organic-anion exuding legumes (eg, Ae et al. 1990; Kamh et al. 1999; Hocking and Randall 2001). Despite being a promising approach to improve the P-use efficiency of cropping systems, little is known about the conditions (soil type, plant species) and mechanisms governing these benefits. The aim of this study was to determine the carry-over P benefits from chickpea, faba bean, white lupin, canola and wheat to a following canola crop. A range of soils labelled with ^{33}P was used to quantify the size of the soil P pools accessed by the crop species (*L* values), and to evaluate the role of P in the break-crop systems.

Methods

Soils

Three soils representing a range of available- and total-P levels were collected from the 0-10 cm layer at Robertson (RB), Grenfell (GF) and Berthong (BT) in NSW. Selected soil characteristics are listed in Table 1. The soils were air-dried and 2-mm sieved prior to use. Five days before sowing, the soils were labelled with carrier-free $^{33}PO_4$ and mixed with the following nutrients (mg/kg soil): K_2SO_4, 223; $CaSO_4$, 255; $MgSO_4$, 230; $MnCl_2$, 37; $ZnSO_4$, 76; $CuCl_2$, 4.2; $(NH_4)_6Mo_7O_{24}$?$4H_2O$, 4.4; H_3BO_3, 5.7; $CoCl_2$?$6H_2O$, 4.1; and NH_4NO_3, 284 (142 mg before sowing, followed by 2 applications of 71 mg during the growing period).

Table 1. Selected site and soil characteristics.

Item	Robertson	Grenfell	Berthong
Soil type	Red Ferrosol	Red Chromosol	Red Kandosol
Land use	Pasture	Rotation cropping	Rotation cropping
pH ($CaCl_2$)	5.1	4.4	5.9
Total C (g/kg)	60	20	23
Total N (g/kg)	5.4	1.7	1.9
Total P (mg/kg)	2660	305	602
Organic P (mg/kg)	1180	110	209
Resin-P (mg/kg)	1.3	3.6	21.5

The ^{33}P-labelled nutrient solution was nebulized onto the soils for 30 min in a modified concrete mixer, and the soil was mixed for a further 2.5 h to ensure homogeneous labelling. About 650 cm^3 of ^{33}P-labelled soil was put into each non-draining plastic pot (82 mm ? 148 mm) and watered to 70% of field capacity before sowing. Subsamples of soil were digested ($HClO_4/HNO_3$) for total P and ^{33}P activity.

Phase 1 - growth of break crops

The plants were grown in a naturally-lit glasshouse maintained at 24/18?C (day/night). The experimental design was a 2-factor randomised block with 5 replicates of each species per soil. Four seeds of white lupin (*Lupinus albus* cv. Kiev Mutant), chickpea (*Cicer arietinum* cv. Amethyst), faba bean (*Vicia faba* cv. Fiesta), wheat (*Triticum aestivum* cv. H45), and canola (*Brassica napus* cv. Hyola 60) were sown per pot. The legumes were not inoculated. Unplanted pots of soil treated in the same way as the planted pots were used as references for phase 2. After emergence, seedlings were thinned to 2 (3 for wheat) uniform plants per pot. The pots were watered daily with deionized water to 75% of field capacity. All plants were grown for 42 days, and then the shoots were cut off at the soil surface and dried at 70?C. After weighing, shoot material was digested (H_2SO_4/H_2O_2) and analyzed for total P and ^{33}P activity.

Phase 2 - canola growth

The root systems of the break crops were allowed to decompose over a period of 21 days after harvesting the shoots, and then all pots (including the unplanted ones) were watered to 70% of field capacity with nutrient solution that supplied (mg/kg soil): K_2SO_4, 112; $CaSO_4$, 148; $MgSO_4$, 115; $MnCl_2$, 19; $ZnSO_4$, 11; $CuCl_2$, 2.1; $(NH_4)_6Mo_7O_{24}$?$4H_2O$, 2.2; H_3BO_3, 2.9; $CoCl_2$?$6H_2O$, 2.2; and NH_4NO_3, 284 (142 mg before sowing, followed by 2 applications of 71 mg during the growing period). Five canola seeds were sown per pot, and the seedlings thinned to 2 uniform plants per pot at 4 to 7 days after emergence. The pots were watered daily as in phase 1. After 42 days, the canola shoots were harvested to determine dry weight, P content and ^{33}P activity.

L-value calculations and statistics

The *L* value (mg P/kg soil), the quantity of soil P available to a plant, was calculated using eqn 1:

$$L = [^{33}P]_{soil} \frac{[^{31}P_{soil}]_{shoot}}{[^{33}P]_{shoot}} \quad (1)$$

where $[^{33}P]_{soil}$ is the activity of ^{33}P added to the soil (kBq/kg), $[^{31}P_{soil}]_{shoot}$ is the concentration of ^{31}P taken up from the soil in the shoot (mg P/g), and $[^{33}P]_{shoot}$ is the activity of ^{33}P in the shoot (kBq/g). Information from the literature and a supplementary experiment (data not presented) was used to correct the shoot P content for seed-derived P to estimate the amount of soil-derived P in the shoot. The effects of soil type and plant species were tested by ANOVA using Genstat 5.

Results

Phase 1 - growth and P uptake by the break crops

Growth, P concentrations and P uptake of canola and wheat were in the order BT>GF>RB, reflecting soil P availability (Table 2). Phosphorus uptake by the P-deficient plants on RB and GF (P concentrations ≤ 1.3 mg/g) corresponded to between 2 and 18% (canola) and between 4 and 8% (wheat) of the P uptake by the P-adequate plants on BT (P concentration > 2.0 mg/g). In contrast, the 3 legumes had better growth and P uptake than canola or wheat on the low-P soils (RB and GF). Compared to RB and GF, P uptake by chickpea, faba bean and white lupin on BT was 5.7- to 5.8-fold, 1.7- to 1.8-fold, and 2.7- to 3.3-fold higher, respectively (Table 2).

Table 2. Shoot dry-matter production, P concentration and P uptake of plants 42 days after sowing. Values for each plant parameter followed by the same letter do not differ significantly (*P* = 0.05).

Species	Shoot biomass (g/plant)			Shoot P concentration (mg/g)			Shoot P uptake (mg/plant)		
	RB	GF	BT	RB	GF	BT	RB	GF	BT
Chickpea	0.55 b	0.50 b	1.06 d	0.80 a	0.86 ab	2.38 f	0.44 c	0.43 c	2.50 f
Faba bean	1.40 ef	1.48 fg	1.94 h	1.18 c	1.17 c	1.55 d	1.64 e	1.72 e	3.00 fg
White lupin	1.37 ef	1.32 e	2.39 j	1.24 c	1.06 bc	1.91 e	1.69 e	1.40 e	4.55 h

Wheat	0.10 a	0.20 a	1.63 g	1.30 c	1.30 c	2.11 e	0.14 a	0.27 b	3.50 g
Canola	0.16 a	0.86 c	3.00 i	0.71 a	1.24 c	2.02 e	0.11 a	1.06 d	5.99 i

White lupin had the highest *L* values, and wheat and canola the lowest (Table 3). On all soils, white lupin accessed a 2- to 3-fold greater pool of P than wheat and canola. The *L* values indicated that chickpea did not access a greater pool of soil P than wheat and canola, despite claims that chickpea is P-efficient because it exudes organic-acid anions from its roots (Veneklaas et al. 2003). On GF and BT, the *L* values for wheat and canola did not differ significantly, indicating these species accessed a similar-sized P pool of 16% (GF) and 22% (BT) of the total soil P, while on RB, the *L* value for wheat was higher than for canola (Table 3). On BT, *L* values for the legumes were in the order white lupin > faba bean > chickpea. The *L* values for faba bean on RB (very low available P) were somewhat compromised because the large ratio of seed P to shoot P uptake made the *L* value calculations very sensitive to the estimated values for seed-derived P accumulated in the shoot. An additional experiment with faba bean and wheat was conducted on RB to obtain a more reliable estimate of the contribution of seed-derived P to total shoot P for calculating *L* values for faba bean. These *L* values indicated that faba bean accessed the same readily available P pool as the wheat. In addition, a solution culture experiment showed that faba bean roots exuded negligible amounts of organic-acid anions and had very low extracellular phosphatase activity under P-deficiency stress (data not presented). It is likely that the large seed reserves of faba bean enable it to develop a vigorous lateral root system early in growth which maximises its ability to explore the soil for available P.

Table 3. *L* values of chickpea, faba bean, white lupin, wheat, and canola in three soils at 42 days after sowing. Values within a soil type followed by the same letter do not differ significantly (*P* = 0.05).

Species	*L* value (mg P/kg soil)		
	RB	GF	BT
Chickpea	331 abc	45 a	137 a
Faba bean	220 ab	40 a	194 b
White lupin	581 c	160 b	235 c
Wheat	217 b	45 a	125 a
Canola	141 a	50 a	134 a

Extraction of the ^{33}P labelled soil from the unplanted pots with organic-acid anions (citrate and malate) showed that a significant proportion of the P taken up by white lupin was likely to have been derived from mineralisation of the enzyme-labile soil organic P pool mobilised by the organic anions exuded from its cluster roots (data not presented).

Phase 2 - growth and P uptake by the subsequent canola

In phase 2, canola grew better after the legumes (especially faba bean) than after wheat or canola (Table 4). On RB, faba bean showed the greatest break-crop effect, followed by white lupin. On GF and BT, there was a large break-crop-benefit of the grain legumes, with growth and P uptake of canola after faba bean, white lupin and chickpea often being 2-fold higher than canola following wheat or canola. The reason for the large increase in growth and P nutrition of canola following faba bean is unknown. However, the effect may be related to the canola roots growing down root channels formed by the large root system of faba bean, and accessing mineralised P from the decomposed faba bean roots.

Table 4. Shoot dry matter, P concentration and P uptake of canola grown after different break-crop species at 42 days after sowing. Values within a column followed by the same letter do not differ significantly (*P* = 0.05).

Prior species	Shoot biomass (g/plant)			Shoot P concentration (mg/g)			Shoot P uptake (mg/plant)		
	RB	GF	BT	RB	GF	BT	RB	GF	BT
Chickpea	0.05 a	0.37 b	1.38 c	0.55 a	1.99 de	2.42 ab	0.03 a	0.73 c	3.31 b
Faba bean	0.13 d	0.62 c	1.08 b	0.84 c	1.68 bc	3.18 c	0.11 d	1.03 d	3.41 b
White lupin	0.08 c	0.39 b	1.11 b	0.69 b	1.56 b	2.86 bc	0.06 c	0.62 c	3.17 b
Wheat	0.06 ab	0.17 a	0.80 a	0.60 ab	1.87 cd	2.80 bc	0.04 ab	0.31 a	2.24 a
Canola	0.05 a	0.21 a	0.84 a	0.60 ab	1.33 a	2.13 a	0.03 a	0.27 a	1.78 a
Bare soil	0.07 bc	0.20 a	1.39 c	0.66 b	2.27 e	2.52 ab	0.05 bc	0.46 b	3.37 b

Conclusions

White lupin was able to access sources of soil P that were less available to chickpea, faba bean, canola and wheat. The legumes had a substantial carry-over benefit on the P nutrition and growth of following canola plants that did not occur when canola followed canola or wheat. It is still unclear whether this is due to P mobilisation by the legumes, or to effects associated with root decomposition.

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