Management of Phosphorus Supply to Australian Floricultural Species

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Abridged title

Management of Phosphorus Supply

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Abstract

Young plants of *Sticherus*, waxflower (*Chamelaucium*) and two *Caustis* cultivars were grown in a soilless potting medium. The plants were fertilised at seven rates of the soluble monocalcium phosphate (MCP) fertiliser and one rate of the slightly soluble rock phosphate (RP). One group of plants was watered by a non-leaching and a second group of plants watered by a leaching method.

Both *Caustis* cultivars (M63, B84) grown in the potting medium under the non-leaching regime did not show deficiency symptoms at no added P, but they showed P toxicity symptoms at MCP-P application rates > 11 g m^{-3}. The critical P concentration in the shoots associated with a 10% decrease in yield from the maximum was 0.26% for *Caustis* M63 and 0.33% for *Caustis* B84. The two *Caustis* cultivars did not develop P toxicity symptoms or show any decline in shoot dry weight when fertilised with RP under both non-leaching and leaching regimes. Leaching reduced but did not eliminate P toxicity in both *Caustis* cultivars, although shoot dry weight did not differ significantly between the two watering regimes used.

Waxflower grew poorly in the potting medium under the non-leaching regime at no added P or when fertilised with RP but did not develop P toxicity symptoms at any rate of P application as MCP, including the highest rate of 352 g m^{-3}. The waxflower plants grew less well under the leaching than when grown under the non-leaching regime. The critical $NaHCO_3$-extractable P level required for production of 90% relative dry weight of shoots of waxflower was about 46 mg kg^{-1} under the non-leaching and about 69 mg kg^{-1} medium under the leaching regime. Under the non-leaching regime the critical

$NaHCO_3$-extractable P level for toxicity of *Caustis* B84 was about 13 mg kg^{-1} while under the leaching regime this was higher at about 22 mg kg^{-1}. *Sticherus* plants did not respond significantly to P application as either MCP or RP. However, *Sticherus* plants grew much better when grown under the leaching than when they were grown under the non-leaching regime. Although leaching conferred some advantages in the growth of *Sticherus* and in the reduction of P toxicity in *Caustis*, it also caused a considerable loss of P.

1. Introduction

When different plant species are grown in a given volume of soil with a given soil solution P concentration, their response is likely to vary depending on the species or cultivar (Moody and Bolland 1999). Difference in P-response is due to species or cultivar characteristics which enable them to cope with low or high levels of P. Phosphorus-sensitive plants are usually those which have evolved in soils low in P. They have efficient mechanisms for P acquisition and utilisation, such as a large highly branched root system (Schachtman et al., 1998), an efficient mechanism of internal P re-distribution (Handreck 1997) and an increased expression of plant phosphate transporter genes (Raghothama 1999).

During domestication, when the P sensitive plants are exposed to high P supply, some species respond by absorbing P 'luxuriously' to toxic levels, while others develop toxicity or deficiency symptoms associated with other plant nutrients (Jones 1998). In contrast, P-insensitive plants respond to high P supply by storing excess P in the vacuole (Raghothama 1999), P efflux across the plant membrane and down-regulation of plant phosphate transporter genes (Smith et al., 2000). The P-uptake and requirements of Australian native plants in the process of domestication are often not known. Native plants that are P-insensitive can tolerate a wide range of P application rates commonly used in commercial horticulture, whereas the P-sensitive plant species cannot. For example, application of superphosphate fertilisers at rates as low as 20 kg P ha^{-1} to Australian heath plants caused death to seedlings of some species (Handreck 1997).

To overcome the problem of under or oversupply of P, it is important to establish the kind of P nutrition response that is exhibited by plants in the process of domestication. This will ensure that the best management strategy for P nutrition is developed for the plant. This paper reports on the P nutrition response of three Australian native plants, *Caustis blakei* (cvs. B84 and M63), waxflower (*Chamelaucium uncinatum* x *C. floriferum* cv. Wanneroo) and *Sticherus flabellatus* (mixed cultivars).

2. Materials and methods

The experiment was conducted at The University of Queensland, Gatton nursery between 22 March 2001 and 20 June 2001 in a polyethylene covered greenhouse. A randomised complete block design with eight different P rates, seven from monocalcium phosphate (MCP) and one from rock phosphate (RP) was used. The P treatments were replicated five times for the two *Caustis* cultivars and waxflower, and three times for *Sticherus*. The experiment was done in two sets; one set under a non-leaching watering regime where watering was done manually to 80% container capacity in sealed pots. The other was under a leaching watering regime, where overhead irrigation was done twice daily at 10.00 am (5 minutes duration) and at 4.00 pm (10 minutes duration) in unsealed pots. This procedure resulted in an average collection of 50 mL leachate /pot/day.

The test species were sorted into groups based on size and numbers of stems so each replicate had plants of a uniform size. They were planted by hand in polythene lined or unlined 17.5 cm (2.6-L) diameter plastic pots containing a commercial potting medium consisting of composted bark-100% and 10% washed sand on a v/v bases (from Growing Media Queensland), which was amended with (in g m^{-3}) 650 KNO_3, 1000 $FeSO_4.7H_2O$, 500 gypsum, 45 chelated micronutrients, 20 $CuSO_4.5H_2O$, 200 NH_4NO_3, 3500 5-6 months Osmocote (NPK 18:0:9.3) and 1500 coated iron. Phosphorus was supplied as MCP- $Ca(H_2PO_4)_2.H_2O$ (24.6%P) at rates of 0, 11, 22, 44, 88, 176 and 352 g m^{-3} and as RP (11.6%P) at the rate of 176 g m^{-3}. The final growing substrate had 62% total porosity (24% air space, 38% water holding capacity), a bulk density of 0.39 g cm^{-3}, a pH (1:5 H_2O) of 4.5 and electrical conductivity (1:5 H_2O) of 2.21 dS m^{-1}.

$NaHCO_3$-extractable P for each P treatment was determined using the procedure described by Colwell (1963). The manual colorimetric finish was based on the method of Murphy and Riley (1962).

The plants were harvested on 20 June 2001 (day 90). The plant shoots were cut off from the base; the roots were removed and washed. The shoots and roots were dried at 60^0C for 72 hours and then weighed. The shoots and roots were ground to pass through a 917-µm mesh screen. Following digestion in a nitric-perchloric acid mixture

(Johnson and Ulrich 1959), the P concentrations in the shoots were determined using a spectroflame model P ICPAES instrument.

Concentration of P in the shoots was plotted against P application rate to determine the responsiveness of the test species to P supply. The relative dry matter yield of the shoots was plotted against P concentration in the shoots and $NaHCO_3$-extractable P to derive a critical P concentration (associated with a 10% decrement from maximum yield) for both deficiency and toxicity.

Every two days, the leachate from three replicate pots of *Caustis* M63 was collected, transferred into a 5 L bottle to which two drops of toluene were added and stored at 4^0 C. Samples of leachate were taken from each of the bottles and filtered through 0.45-μm millipore membrane filters to remove large particles. Phosphorus concentration in the leachate was determined by a spectroflame model P ICPAES instrument. The quantity of P leached per pot was obtained by multiplying the P concentration (mg L^{-1}) by the volume of leachate (L) collected over the 90 days duration of the experiment.

Analysis of data

All data was analysed using the general linear model of the Minitab (Release 13.1) statistical package; LSDs (0.05) were calculated. Response curves were plotted using Sigma Plot and Excel.

3. Results

3.1. Plant growth

There was an interaction between P treatments and watering regime for *Caustis* and waxflower (Figure 1), but not for *Sticherus*. Under the non-leaching regime, growth of both *Caustis* cultivars decreased with increase in MCP application. In contrast, growth of waxflower increased with increase in MCP application. Under the leaching regime, *Caustis* B84 had a similar response to P as under the non-leaching regime. However, there was a less marked effect of P on *Caustis* M63. Waxflower responded similarly to MCP under both the non-leaching and leaching regimes, but the yield plateau reached was much reduced under leaching.

Insert Figure 1

Root dry weight for *Caustis* and *Sticherus* declined, but that of waxflower increased to a maximum, with increasing P application, under both watering regimes (data not shown). Root dry weight of both *Caustis* cultivars was much greater when P was supplied as RP than when supplied as MCP at 176 g m^3; the opposite effect occurred with waxflower while there was no effect of P source on *Sticherus* (data not shown). The maximum root dry weight of plants in the leaching regime was about 70% of that attained in the non-leaching regime; the exception was *Sticherus* which achieved greater root growth when grown under the leaching regime.

Phosphorus source had a significant effect on growth of the test species depending on the watering regime (Figure 2). Under the non-leaching regime, waxflower grew much better than *Caustis* and *Sticherus* when P was supplied as MCP. *Caustis*, particularly B84, grew better than waxflower and *Sticherus* with RP. Under the leaching regime with MCP, *Caustis* and *Sticherus* grew better and waxflower less well. With RP, *Caustis* performed equally as well as under the non-leaching regime, while *Sticherus* and waxflower grew poorly.

Insert Figure 2

3.2. Phosphorus concentration in the shoots

Concentration of P in shoots varied with the species and watering regime (Figure 3). Under the non-leaching regime, there was a large increase in P concentration in shoots of *Caustis* with increased rate of MCP application. *Sticherus* and waxflower showed a much lower increase in P concentration in shoots with increased rate of MCP. Under the leaching regime, the response in P concentration in the shoots to MCP application followed a similar pattern, although in the case of *Caustis* and waxflower values were considerably depressed.

Insert Figure 3

3.3. Phosphorus toxicity symptoms with MCP application

With MCP application, toxicity symptoms appeared in *Caustis* under both watering regimes and in *Sticherus* under the non-leaching regime, but not in waxflower. In *Caustis*, the symptoms first appeared in the non-leaching regime on day 20 and 25 for cultivar B84 and M63 respectively, at the highest MCP-P application rate. By day 50, the symptoms had spread to most *Caustis* plants except those receiving less than 22 g m^{-3}. The symptoms started with older leaves becoming pale yellow, followed by the drying of the leaf tips and ultimate branchlets. The drying spread downward from the leaf tips and ultimate branchlets resulting in the whole plant having a 'burnt up' appearance. The P toxicity symptoms in *Caustis* under the non-leaching regime were more severe than those under the leaching regime. The symptoms appeared to increase as the P concentration in *Caustis* shoots increased. Toxicity symptoms in *Sticherus*, which were characterised by drying of whole leaf fronds, first appeared on day 15, starting in the treatment that received 176 g m^{-3} under the non-leaching regime. *Sticherus* leaf fronds started drying gradually leaving no green material on the plant. The frond drying continued throughout the period of the experiment in all P treatments under the non-leaching regime except those receiving MCP-P at rates of 44 and 352 g m^{-3}. The *Sticherus* plants under the leaching regime did not have toxicity symptoms.

3.4 $NaHCO_3$-extractable P in the potting medium

A small amount of $NaHCO_3$-extractable P (13.3 mg kg^{-1}) was present in the potting medium before the addition of the P treatments. For the MCP fertiliser, $NaHCO_3$-extractable P increased as the level of P application increased (Figure 4). At relatively low levels of MCP supply ($\leq$ 22 g m^{-3}), $NaHCO_3$-extractable P increased less rapidly per unit of applied P than it did at the higher levels of MCP supply; this suggests that there was some buffering effect of the potting medium at low levels of MCP supply. This may explain why *Caustis* plants did not show P toxicity symptoms at these levels of P supply. Supply of P as RP at a rate equal to the second highest MCP rate hardly changed the $NaHCO_3$-extractable P from that of the zero rate. This suggests that RP is a very slow release fertiliser that can be suitable for P-sensitive plants that may not have a mechanism of regulating P uptake.

Insert Figure 4

3.5. Management of P toxicity with RP

Under the non-leaching regime, there was a much lower shoot P concentration in *Caustis* grown with RP than with MCP (Table 1). There was little difference in shoot P concentration between *Sticherus* and waxflower across RP versus MCP. Under the leaching regime, there was a similar pattern, but the P concentrations were much lower. No symptoms of P toxicity on *Caustis* were observed with application of RP.

Insert Table 1

However, the effectiveness of RP in the P nutrition management was dependent on the plant species. Waxflower plants had a lower shoot weight when fertilised at 176 g m^{-3} as RP than with MCP (Figure 2), a result consistent with that of Gilbert et al. (1990) who worked on pasture plant species. There was no significant difference in the shoot weight of *Sticherus* fertilised at 176 g m^{-3} as either RP or MCP while both *Caustis* cultivars had a higher shoot weight when fertilised with RP at 176 g m^{-3} than when fertilised with MCP (Figure 2). It would appear that fertilising *Caustis* with RP would have some advantages over the use of soluble MCP especially where soilless media are used.

3.6. Critical P concentrations

The critical P concentrations corresponding to deficiency and toxicity were determined for waxflower and the two *Caustis* cultivars (Table 2, Figure 5) but not for *Sticherus* because its growth did not respond significantly to the application of P. Under the non-leaching regime, the critical P concentrations for deficiency did not differ greatly between the two *Caustis* cultivars (0.04 and 0.07 %), while the critical concentrations for toxicity (0.26 and 0.33%) were likewise not greatly different (Table 2). However, the critical P concentration for deficiency in waxflower was somewhat higher at 0.17%, while no critical concentration for toxicity was obtained in that species.

Insert Table 2 and Figure 5

Under the leaching regime, the critical P concentration of the two *Caustis* cultivars was different. *Caustis* M63 had a considerably higher critical P concentration associated with both deficiency and toxicity than did *Caustis* B84 (Table 2). The response by waxflower was similar to that in the non-leaching regime although the maximum dry matter yield produced was about one-half that produced under the non-leaching regime.

3.7. Critical $NaHCO_3$-extractable P level

Waxflower exhibited a critical $NaHCO_3$-extractable P level for deficiency of about 46 and 69 mg kg^{-1} under non-leaching and leaching regimes, respectively (Figure 6). Waxflower did not develop any P toxicity symptoms or show any reduction in growth at high levels of $NaHCO_3$-extractable P. Under the non-leaching and leaching regimes, the $NaHCO_3$-extractable P level associated with toxicity of *Caustis* B84 was low at about 13 and 22 mg kg^{-1}, respectively (Figure 6). It was not possible to determine a critical NaHCO3-extractable P level for deficiency in *Caustis* B84; however, the data suggest a very low value is likely. No critical P level for toxicity has been obtained for *Caustis* M63 because of the variability of the data, particularly under the leaching regime.

Insert Figure 6

3.8. Leaching of P

There was a substantial loss of P (Table 3) and other nutrients (data not shown) from the potting medium under the leaching regime with the soluble MCP. The loss of P through leaching increased significantly with increasing application of MCP. At the highest rate of P application (352 g m^{-3}) as MCP, 43% of the P applied was lost through leaching over the 90 days duration of the experiment (Table 3). Minimum leaching of P from the RP treatment (Table 3) indicated that P was released more slowly from that source than from the soluble MCP. Most of the essential nutrients in the potting medium were provided as soluble salts; hence, they were more vulnerable to leaching. The loss of the nutrients through leaching was reflected in the lower shoots weight of waxflower plants grown under the leaching regime than those grown under the non-leaching regime (Figure 1). This suggests that waxflower is a salt tolerant species and while anecdotal information supports this suggestion, no published research exists.

Insert Table 3

4. Discussion

4.1. The response of Sticherus*, waxflower and* Caustis *to phosphorus nutrition*

A closer examination of the three Australian floricultural species indicated that they exhibited different P nutrition responses and thus required different P nutrition management strategies. The two *Caustis* cultivars were shown to be P sensitive while waxflower and *Sticherus* were not. Waxflower and the *Caustis* cultivars (M 63, B84) showed some response to the source of P while *Sticherus* did not.

Both *Caustis* cultivars were able to regulate P uptake at low MCP application rates, but were unable to maintain this control when MCP-P application was excessive (> 22 g m^{-3}). Moreover, *Caustis* was found to be efficient in internal P utilisation, as indicated by the low critical P concentration (0.04 and 0.07% P for *Caustis* 'M63' and 'B84' respectively) required to attain 90% relative yield (Table 2). *Caustis* B84 plants grown at low P application (≤ 11 g m^{-3}) as MCP or with RP at 176g m^{-3} had a relatively high root dry weight compared to the plants grown at moderate to high P (≥ 44 g m^{-3}) application rates (data not shown). The high root biomass at the low P application rates appeared to have allowed extensive foraging of P to occur from the potting medium. Allocation of relatively higher biomass to roots at low P availability has been reported in common bean (Nielsen et al., 2001), chrysanthemum (Hansen and Lynch 1998) and in tomato (Coltman, 1987). Nielsen et al., (2001) and Hansen and Lynch (1998) reported that shoot growth in the common bean and chrysanthemum was retarded at low P application, suggesting that the increased root biomass developed at the expense of shoot weight. In one experiment, Nielsen et al., (2001) found that shoot growth in common bean plants provided with a constant low P concentration (0.031 mg L^{-1}) in the soil solution was reduced by more than 90% when compared to plants provided with a constant high soil solution P concentration (0.93 mg L^{-1}). In contrast, both *Caustis* cultivars grown at low P application as MCP in the potting medium did not show a significant shoot weight reduction despite the relatively high root weight (Figure 1). Therefore, the relatively high root weight in the *Caustis* plants grown at low P application ($\leq$ 11 g m^{-3}) did not appear to be at the expense of the shoot growth. An inability to regulate P uptake when excess P was applied, coupled with the development of P toxicity symptoms and a strong reduction in growth was consistent with the relatively high P concentration in the whole shoots of both *Caustis* cultivars grown at moderate to high P rates of P application ($\geq$ 22 g m^{-3}) as MCP.

The concentration of P in the shoots of waxflower grown under the non-leaching regime with no added P was not greatly different to that of both *Caustis* cultivars grown in the same regimes. However, the waxflower grown with no added P had a lower relative dry matter yield than that of both *Caustis* cultivars grown in the same conditions (Figure 6). This indicates that waxflower has poor internal P utilisation mechanisms compared to *Caustis* plants. Further evidence of poor internal P utilisation for waxflower was indicated by the relatively high $NaHCO_3$-extractable P level (90 and 100 mg kg^{-1}) required to produce 90% relative shoot dry weight in waxflower grown under non-leaching and leaching regimes. Unlike *Caustis*, waxflower was able to regulate P uptake at higher P application rates, which was indicated by the almost unchanged concentration of P in the shoots, as P application as MCP was increased (Figure 3). *Sticherus* was able to regulate P uptake at both low and high P application rates. For

Sticherus grown under the non-leaching and leaching regimes, the concentration of P in the shoots and the weight of the shoots were not significantly different at all P application rates (Figure 3). Because of their differences in P nutrition response, the three floricultural species would require different approaches in their P nutrition management.

4.2. Leaching and the management of P nutrition

Leaching produced varied responses among the three floricultural species. *Sticherus* plants had a higher mean shoot and root weight under the leaching than those grown under the non-leaching regime. In contrast, waxflower plants grown under the leaching had a lower mean shoot weight than those grown under the non-leaching regime. The mean concentration of P in the shoots and the extent of P toxicity was lower in *Caustis* plants grown under the leaching than in plants grown under the non-leaching regime. While leaching appeared to confer some advantages to the growth of *Sticherus* and a reduction of P toxicity in *Caustis,* it also resulted in considerable leaching of P (Table 3) and other essential nutrients (data not shown) from the potting medium. The high loss of nutrients through leaching was probably due the limited nutrient retention capacity of the composted bark-based potting medium (Fox and Kamprath 1970, Marconi and Nelson 1984, Cole and Dole 1997, Huett 1997). Cole and Dole (1997) found that 47% of the P applied as single superphosphate to 1 L pots containing a 3 composted pine bark: 1 peat: 1 sand substrate was lost by leaching within 14 days when each pot was watered daily with 250 mL deionised water. The P concentration in the leachate collected over the 90 days duration of the experiment ranged from 0.3 mg L^{-1} with no added P to 76.3 mg L^{-1} with 352 g m^{-3} of P applied as MCP (Table 3). The concentration of P in the leachate collected from the potting medium fertilised with RP ($176\ g\ m^{-3}$) was lower ($0.38\ mg\ L^{-1}$) than that of leachate from the medium fertilised with MCP ($27.8\ mg\ L^{-1}$) at the same rate of P application (Table 3). These results showed that RP could be used to manage P nutrition of P sensitive plants like *Caustis* grown in a soilless medium under a leaching regime with minimal loss of P in the leachate.

The loss of P and other essential nutrients through leaching is not only an economic loss to the grower, but can be a source of pollution to waterways. It has been estimated that P concentrations that can trigger eutrophication and growth of toxic algal blooms in waterways can be as low as $0.02\text{-}0.035\ mg\ P\ L^{-1}$ (Heckrath *et al*. 1995, Turner and Haygarth 1999).

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Table 1. Phosphorus concentration in whole shoots of *Caustis*, *Sticherus* and waxflower grown at 176 g m^{-3} supplied as MCP and RP, under non-leaching and leaching regimes.

Table 2. Critical P concentration in plant shoots required to produce 90% of the maximum shoots yield at deficiency and toxicity limits for waxflower and *Caustis* (M63 and B84) grown under non-leaching and leaching regimes.

Table 3. Effect of fertiliser source (MCP or RP) and rate of soluble fertiliser (MCP) application (applied at planting) on the leaching of P from the potting medium after 90 days of daily overhead irrigation on *Caustis* M63.

Table 1

	P concentration in whole shoots (%)			
	Non-leaching		Leaching	
	MCP	RP	MCP	RP
Species				
Sticherus	0.13	0.03	0.09	0.06
Waxflower	0.47	0.15	0.23	0.11
Caustis M63	2.1**	0.11	1.01*	0.11
Caustis B84	2.0**	0.10	0.61*	0.09

* Moderate P toxicity symptoms   ** Severe P toxicity symptoms

Table 2.

	Critical P concentration (%)			
	Non-leaching		Leaching	
	Deficiency	Toxicity	Deficiency	Toxicity
Species				
Waxflower	0.17	n.a.	0.12	n.a.
Caustis M63	0.04	0.26	0.21	0.54
Caustis B84	0.07	0.33	0.05	0.17

n.a. indicates 'not applicable'

Table 3.

P applied g m^{-3}	P applied mg/pot	Mean P conc in leachate mg L^{-1}	P leached mg/pot	Adjusted P leached mg/pot	% P leached
0	0.0	0.3	1.2	0.0	0.0
11 (MCP)	28.6	0.6	2.9	1.7	5.9
22 (MCP)	57.2	0.9	4.8	3.6	6.3
44 (MCP)	114.4	6.4	26.0	24.7	21.6
88 (MCP)	228.8	7.9	33.4	32.2	14.1
176 (MCP)	457.6	27.8	122.0	120.7	26.4
176 (RP)	457.6	0.38	1.7	0.4	0.1
352 (MCP)	915.2	76.3	398.1	396.9	43.4
Significance	-	***	***	-	**
LSD (P=0.05)	-	14.5	117.3	-	15.8

** P value <0.01; *** P value <0.001

conc – concentration.

Adjusted P leached - obtained by subtracting P leached from potting medium with no added P from the total P leached from potting medium fertilised at different P rates.

Figure 1. Shoot dry weight response by *Sticherus* (●) waxflower (■), *Caustis* 'M63' (σ) and *Caustis* 'B84' (τ) to different levels of P, supplied as MCP fertiliser under the non-leaching and the leaching watering regime. Each data point is the average of three plants for *Sticherus* and five plants for the other species.

Figure 2. Effect of P source on shoot dry weight of *Sticherus* (Sti), waxflower (Wax), *Caustis* 'M63' (C-M63) and *Caustis* 'B84' (C-B84), when applied as MCP or RP fertiliser at rate of 176 g P m^{-3} medium under the non-leaching and the leaching watering regime. Each data point is the average of three plants for *Sticherus* and five plants for the other species.

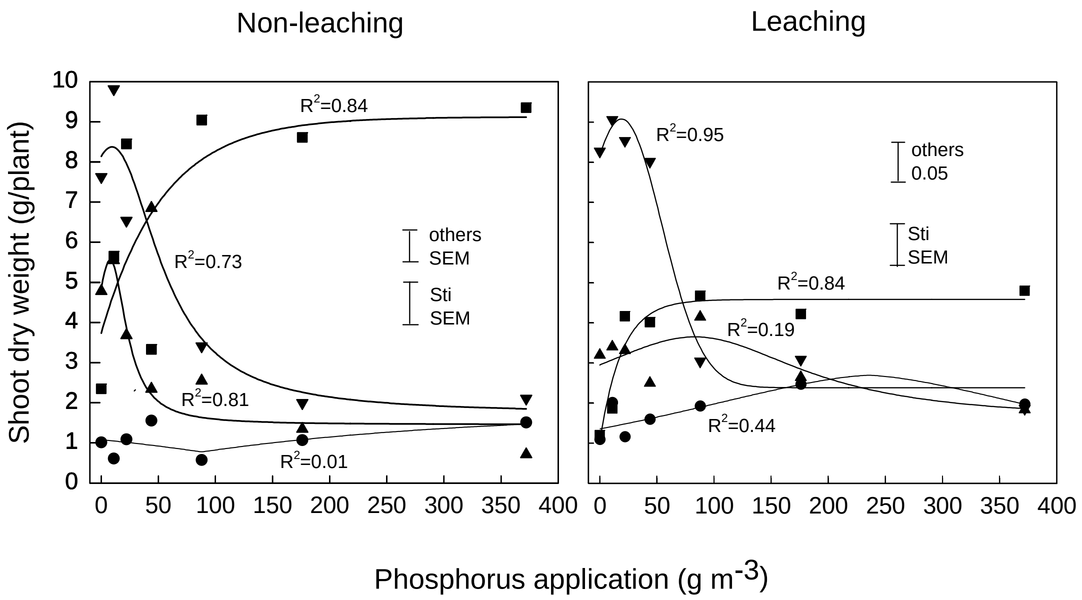
Figure 3. Concentration of P in the whole shoots of *Sticherus* (●), waxflower (■), *Caustis* 'B84' (τ) and *Caustis* 'M63' (σ) at different levels of P, supplied as MCP fertiliser under the non-leaching and the leaching watering regime. Each data point is the average of three plants for *Sticherus* and five plants for the other species.

Figure 4. Effect of type (supplied as MCP or RP) and level of P fertiliser supply on level of $NaHCO_3$-extractable P in the potting medium

Figure 5. Relationship between relative dry matter yield and concentration of P in the shoots of waxflower (■), *Caustis* M63 (σ) and *Caustis* B84 (τ) grown for 90 days under non-leaching and leaching regimes. Each data point is the average of three plants for *Sticherus* and five plants for the other species.

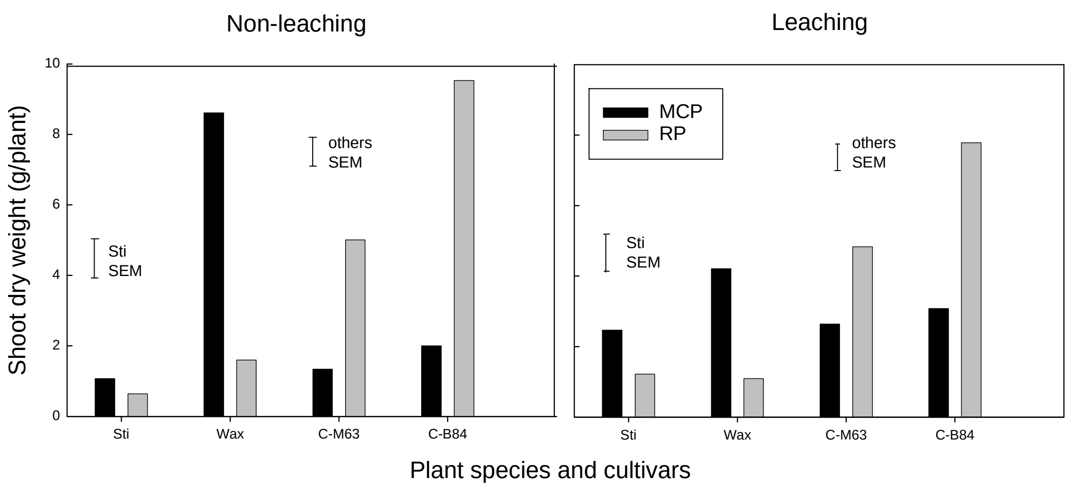
Figure 6. Relationship between relative dry matter yield of shoots and $NaHCO_3$-extractable P for waxflower (■) and *Caustis* B84 (■) grown for 90 days under non-leaching and leaching. Each data point is the average of five plants.

Figure 1



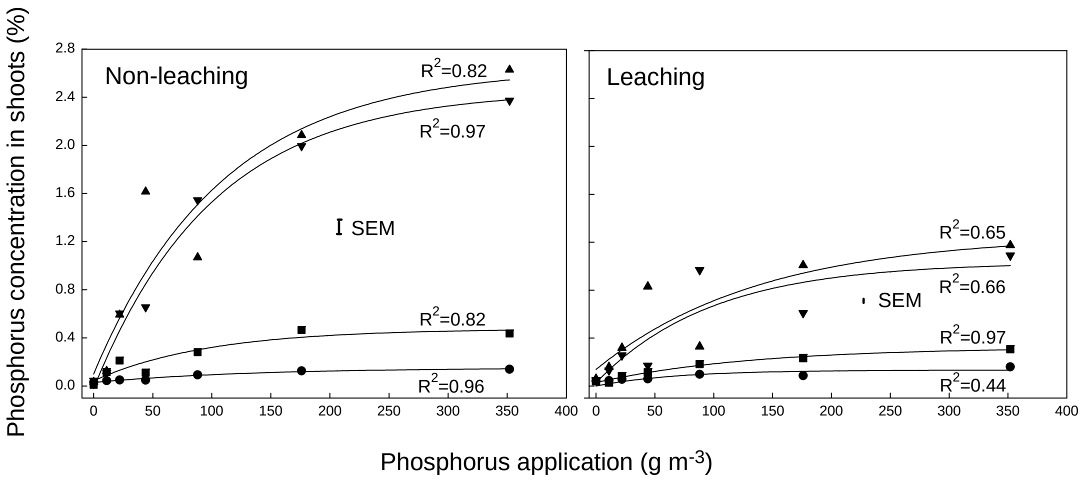
Non-leaching
Leaching
Shoot dry weight (g/plant)
10
9
8
7
6
5
4
3
2
1
0
R²=0.84
R²=0.73
R²=0.81
R²=0.01
others
SEM
Sti
SEM
R²=0.95
others
0.05
Sti
SEM
R²=0.84
R²=0.19
R²=0.44
0 50 100 150 200 250 300 350 400
0 50 100 150 200 250 300 350 400
Phosphorus application (g m⁻³)

Figure 2



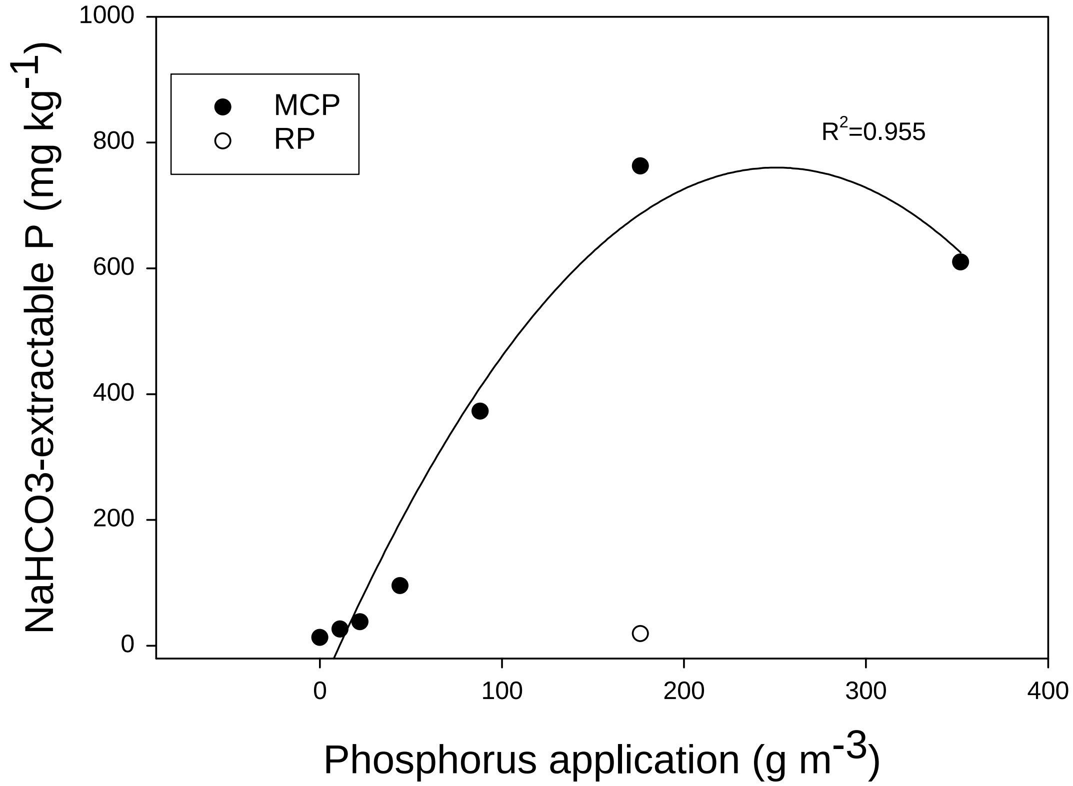
Non-leaching
Leaching
Shoot dry weight (g/plant)
10
8
6
4
2
0
MCP
RP
others
SEM
Sti
SEM
Sti
Wax
C-M63
C-B84
Plant species and cultivars

Figure 3



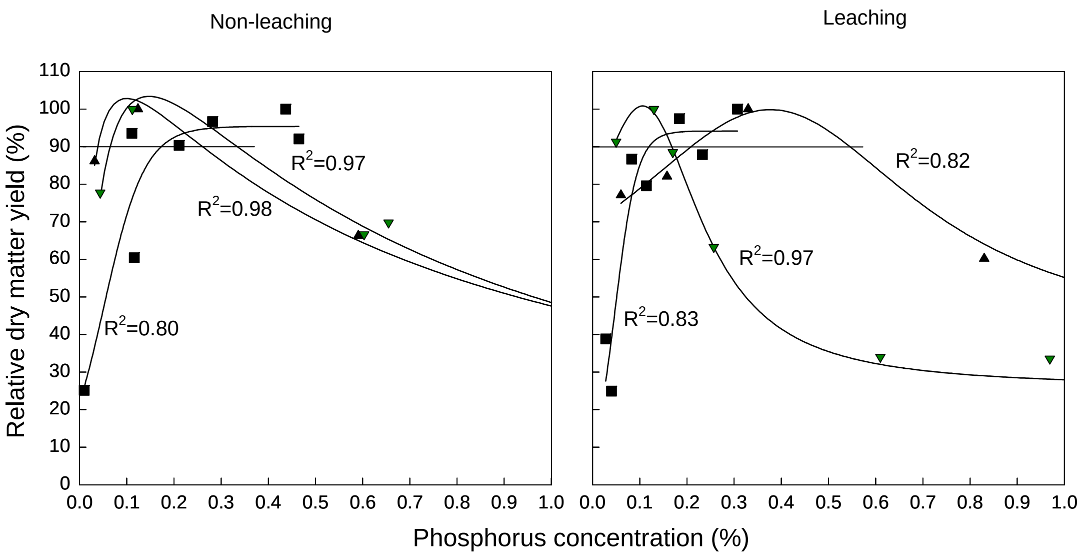
Phosphorus concentration in shoots (%)
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0
Non-leaching
R^2=0.82
R^2=0.97
SEM
R^2=0.82
R^2=0.96
Leaching
R^2=0.65
R^2=0.66
SEM
R^2=0.97
R^2=0.44
0 50 100 150 200 250 300 350 400
0 50 100 150 200 250 300 350 400
Phosphorus application (g m^{-3})

Figure 4



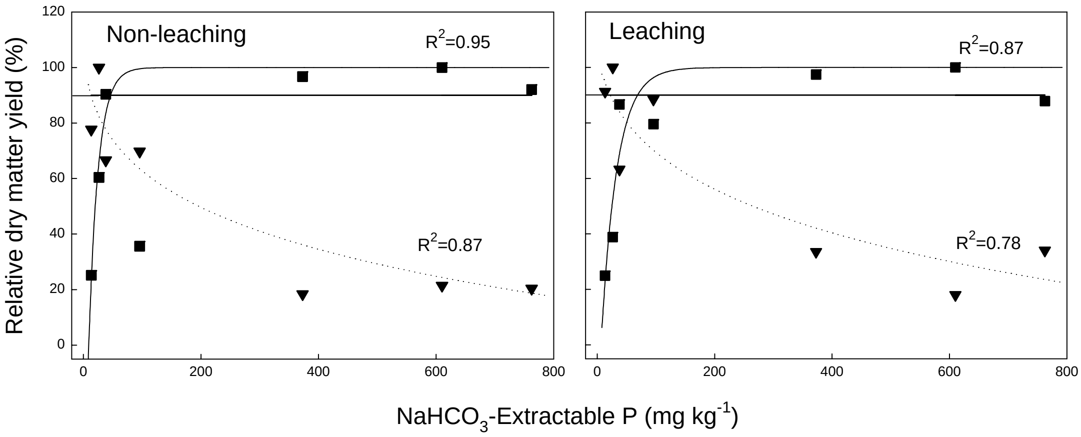
1000
800
600
400
200
0
NaHCO3-extractable P (mg kg-1)
MCP
RP
R2=0.955
0
100
200
300
400
Phosphorus application (g m-3)

Figure 5



Non-leaching
Leaching
Relative dry matter yield (%)
Phosphorus concentration (%)
R2=0.97
R2=0.98
R2=0.80
R2=0.82
R2=0.97
R2=0.83
0
10
20
30
40
50
60
70
80
90
100
110
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

Figure 6



Non-leaching
Leaching
R^2=0.95
R^2=0.87
R^2=0.87
R^2=0.78
Relative dry matter yield (%)
0
20
40
60
80
100
120
0
200
400
600
800
NaHCO$_3$-Extractable P (mg kg^{-1})