PHOSPHORUS RESPONSE AND EFFICIENCY OF 12 NOVEL DRYLAND LEGUME SPECIES ON AN ACID HIGH COUNTRY SOIL

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Abstract

High country soils are typically acidic and have low fertility compared with intensive high fertility low land systems. Pasture legumes commonly used in New Zealand perform poorly in these environments. The optimum soil P status for growth of many potential alternative legume species for this environment is unknown.

Twelve legume species were grown under glasshouse conditions at Lincoln University in an acidic high country soil (Ashwick stoney / boldery silt loam) from the Lees Valley (North Canterbury). Phosphorus was applied at eight rates (0, 10, 30, 60, 100, 250, 500, 1500 mg P kg^{-1} soil). Plants were harvested monthly post establishment and the yield determined. Annual species grew on average for 25 weeks, while perennial species grew for 42 weeks. Herbage was analysed for macro and micro element content and uptake. Soils were analysed for available P content at the end of the experiment.

Phosphorus increased the yield of both annual and perennial legume species through the increase in plant available P. Optimum Olsen P for maximum yield differed between species as did P use efficiency. Persian clover was the highest yielding annual species (13.6 g DM pot^{-1}) followed by subterranean clover > arrowleaf clover > balansa clover, while gland clover was the lowest yielding annual species (1.2 g DM pot^{-1}). Lotus was the highest yielding perennial species (15.0 g DM pot^{-1}) followed by tagasaste > lucerne > Caucasian clover > falcata lucerne > strawberry clover, while white clover was the lowest yielding perennial species (8.2 g DM pot^{-1}). As a measure of P use efficiency, the Olsen P at which biological optimum (97%) yields were achieved varied between species, ranging from 21 mg L^{-1} (tagasaste) to 174 mg L^{-1} (gland clover). Gland, balansa and arrowleaf clovers had the lowest P use efficiency, while tagasaste, white and Persian clovers had the highest. Arrowleaf, subterranean and balansa clovers gave the greatest increase in yield at low P inputs (100 mg P kg^{-1}). Further research using field trials is required to confirm these results under natural climatic and physical conditions.

Introduction

The hill and high country of New Zealand is extensively farmed and in terms of productivity often has a short, moisture limited production season. The soils are typically acidic, with low available phosphorus (P) and sulphur (S) which influences the growth and persistence of legumes (Haynes & Williams 1993; Moir et al. 2000).

Legumes play a key role in New Zealand agriculture, contributing nitrogen (N) to the system as well as increasing the quality of feed, for improved animal performance (Brown & Green 2003). N is often the most limiting nutrient for pastures, while the amount of N fixed from the atmosphere and added to the soil by legumes is significant and may be the only nitrogen input to the system. There is extensive literature on the optimum growth conditions of white clover (Trifolium repens) (Black et al. 2000; During & Brier 1973; Lowther & Adams 1970), the most commonly sown clover in New Zealand but it is poorly suited to dryland low fertility conditions. Subterranean clover (Trifolium subterranean) has also been researched for this environment (Brown et al. 2006; Hayes et al. 2008). However, farmers require a more diverse range of both perennial and annual legume species for their dryland farming systems (Brown & Green 2003). There is little available information on many other potential species for the hill country environment in terms of optimum soil or nutrient conditions for growth.

Phosphorus is required at higher concentrations for legumes to grow and compete with grasses (Caradus 1980). Adequate plant-available soil P is critical for their production and persistence. P has been aerially applied to the high country in the form of super phosphate for over 50 years (Gillingham et al. 1999). However, due to the economics of this practice most high and hill country soils are deficient in P. For this reason species which perform well in low P soils are valuable for this type of production system and environment.

A glasshouse experiment was conducted to quantify legume response to applied P under controlled climatic conditions. The objective of this study was to determine the effects of P addition on the growth and nutrient uptake of 12 legume species grown in an acid high country soil from the Lees Valley in North Canterbury. The hypothesis being tested in this experiment is that the growth and nutrient uptake will differ between species with different soil P status.

Materials and Methods

Soil Collection and Preparation

Soil (0–0.2 m depth) was collected from a hill/ high country site (48° 08' 25" South. 172° 11' 20" East) on 'Mt Pember Station' in the Lees Valley, North Canterbury, New Zealand in May 2010. The soil is a high country yellow brown shallow stony soil (NZ classification: Orthic brown soil, (Hewitt 1998); USDA: Dystrochrept, (Soil Survey Staff 1998)). The site altitude is 430 m a.s.l. with a mean annual rainfall of 600 mm, which mainly falls in winter and early spring. This high country site has had no regular farm management strategy (fertiliser inputs) for improving soil fertility. The soil was prepared by passing it through a 4 mm sieve while field moist, removing all plant material, and then mixing thoroughly. Soil subsamples were analysed and indicated a low fertility status of Olsen P 9 mg L^{-1}, sulphate S 6 mg kg^{-1}, pH 5.1.

Experimental Design and Management

A pot trial was conducted under glasshouse conditions at the Lincoln University glasshouse facility. This pot trial examined 12 species of pastoral legumes, grown at eight rates of phosphorus, replicated four times. Basal lime was incorporated to adjust soil pH to 6.0. The 12 legume species sown are commonly used in NZ high country, or could potentially be grown there. The legume species examined were: Arrowleaf clover (*Trifolium vesiculosum*; West Coast Seed (Aus) cv. 'Cefalu'); Balansa clover (*Trifolium michelianum*; Seed Mark cv. 'Bolta'); Caucasian clover (*Trifolium aumbiguum*; Pgg Wrightsons cv. 'Endura 3'); Gland clover (*Trifolium glanduliferum*; Kiwi Seed Co. cv. 'Prima'); Lotus (*Lotus pedunculatus*; Tai Tapu, Selwyn district cv. 'Maku'); Lucerne (*Medicago sativa*; Seed Force cv. 'Force 4'); Persian clover (*Trifolium resupinatum*; Specialty Seeds cv. 'Enrich'); Falcata lucerne (*Medicago falcate*; Kiwi Seed Co.); Subterranean clover (*Trifolium subterraneum*; Kiwi Seed Co. cv. 'Mt Barker'); Strawberry clover (*Trifolium fragiferum;* Gentos cv. 'Lucila');

Tagasaste (*Chamaecytisus proleferus;* collected near Lincoln, Selwyn district); White clover *(Trifolium repens*; Grasslands cv. 'Nomad').

Pots (9.5 cm deep 10 cm diameter) were used, containing 600 g of field moist soil. P was incorporated at rates of 0, 10, 30, 60, 100, 250, 500, 1500 mg P kg^{-1} soil. The soil was wetted and seeds were sown at 10 seeds pot^{-1} in June 2010 (later thinned to 5 plants pot^{-1}). During the experiment a total of 200 kg S ha^{-1} and 500 kg K ha^{-1} equivalent was applied as basal nutrient solutions (Booking 1976; Caradus & Snaydon 1986). In mid July (four weeks post germination), a small quantity of N (30 kg N ha^{-1} equivalent) nutrient solution was also applied, in the form of ammonium nitrate (NH_4NO_3). This was applied to all pots to overcome any plant N deficiencies during the seedling establishment phase. Beyond this point, plants were dependant on N sourced from N fixation or soil N for growth. The pots were also inoculated with commercial (diluted peat culture) rhizobia strains ('Nodulaid'; Becker Underwood Ltd, Australia) appropriate to each legume species 16 days post germination. Pots were watered daily to 35-40% volumetric water capacity which represented a soil which was neither waterlogged nor dry. The mean daily temperature for the trial period was 19.4°C with daily average temperatures ranging between 16.2 and 23.9°C.

Measurements and Data Analysis

Plants were harvested every four to five weeks, to maximise shoot yield, but prevent flowering. A total of seven harvests were performed from September 2010 to March 2011. Generally the annual species had three harvests before going to seed and dying as expected from the physiology of annual legume species. In addition three species (arrowleaf, balansa and gland clovers) had a shorter total growth period and for that reason were harvested only once or twice during the experiment, hence these three species were lower yielding for that reason. The different species were harvested using different cutting techniques, dependant on the growth habit of the particular species.

Herbage samples were oven dried (70°C for 48 hours), weighed, ground, digested and analysed for a complete range of elements (excluding N) using ICP-OES analysis (Varian 720-ES ICP-OES; Varian Inc., Victoria, Australia). All soil samples were analysed for Olsen P status at the completion of the experiment.

Data were tested for treatment effects by conducting an analysis of variance (ANOVA) using Genstat version 13.0 (VSN International). The model included plant species, P rate and species x P rate interaction as fixed effects, with shoot yield, shoot P concentration and P uptake as random effects. Regression analysis (curve fitting) was used to understand these relationships.

Results

Yield

A strong difference ($P < 0.001$) in dry matter (DM) yield was observed with increasing rates of phosphorus. The mean total shoot yield ranged from 0.2 g DM pot^{-1} (gland clover) to 11.3 g DM pot^{-1} (lotus) (Figure 1). The mean DM yield across all P treatments for the annual species ranged from 0.2 g DM pot^{-1} (gland clover) to 10.1 g DM pot^{-1} (Persian clover). Gland clover was the lowest yielding species overall, and the other annual species produced more DM ($P < 0.001$). In terms of the perennial species, mean DM yields across all P treatments ranged from 6.1 g DM pot^{-1} (white clover) to 11.3 g DM pot^{-1} (lotus). Lotus and tagasaste were much more productive than the other perennial species. In most cases the perennials produced a greater total DM yield than the annual clovers. The maximum yield across all species was at the 500 mg P kg^{-1} P rate (Olsen P = 58) with 8.2 g DM pot^{-1}. On average the greatest increase in DM yield was between 30 and 60 mg P kg^{-1} soil (1.0 g DM pot^{-1}). There was a strong ($P < 0.001$) species by P rate interaction. This interaction effect indicates that the way in which the plants responded to the increased P rate differed among species. For this reason the relationship between increased P rate and DM yield was examined in more detail using regression analysis of the data for individual species.

Most annual species followed a typical 'rise to maximum' yield response curve with increasing P rate. Yield was strongly associated (R^2 = 0.93 – 0.98) with P rate (Figure 1). The exception was gland clover, where the relationship between yield and P rate was best explained by an exponential curve function (R^2 = 0.97; Figure 1). The perennial species all followed a 'rise to maximum' curve with increasing P inputs, and again, these relationships were very strong (R^2 = 0.90 – 0.98; Figure 1). At 0 mg P kg^{-1} lotus, Persian clover and tagasaste were the highest yielding species at 8.0, 7.0 and 6.4 g DM pot^{-1}. Gland, arrowleaf, balansa and subterranean clovers were the lowest yielding species at 0, 0.5, 0.5 and 0.9 g DM pot^{-1}. At 1500 µg P pot^{-1} lotus, tagasaste and lucerne were the highest yielding species at 15.0, 13.0 and 12.1 g DM pot^{-1}. Gland, balansa and arrowleaf clovers were the lowest yielding at 1.2, 1.4 and 1.8 g DM pot^{-1}. At just 100 mg P kg^{-1} arrowleaf clover, subterranean clover and balansa clover gave the greatest response in yield from the control treatment.

P Efficiency

The 97% maximum DM yield of each species was calculated as a measure of biological maximum relative yield, and values are presented in Table 1. The maximum yield (97%) along with the P rate at this yield indicates P use efficiency. Of the annual species the greatest 97% maximum yield ranged from 1.1 g DM pot^{-1} (gland clover) achieved at 1465 mg P kg^{-1} to 12.9 g DM pot^{-1} (Persian clover) achieved at 369 mg P kg $^{-1}$ (Table 1). Subterranean clover achieved a 97% maximum yield of 4.2 g DM pot^{-1} at just 336 mg P kg^{-1}. Of the perennial species the 97% yield ranged from 7.8 g DM pot^{-1} at 203 mg P kg^{-1} (white clover) to 14.3 g DM pot^{-1} at 440 mg P kg^{-1} soil (lotus). Interestingly, tagasaste produced 12.6 g DM pot^{-1} at just 132 mg P kg^{-1} soil while white clover produced 7.8 g DM pot^{-1} at 202 mg P kg soil^{-1}. The shoot P concentration at 97% yield was highest for falcata lucerne at 0.39% while tagasaste was the lowest at 0.23% P.

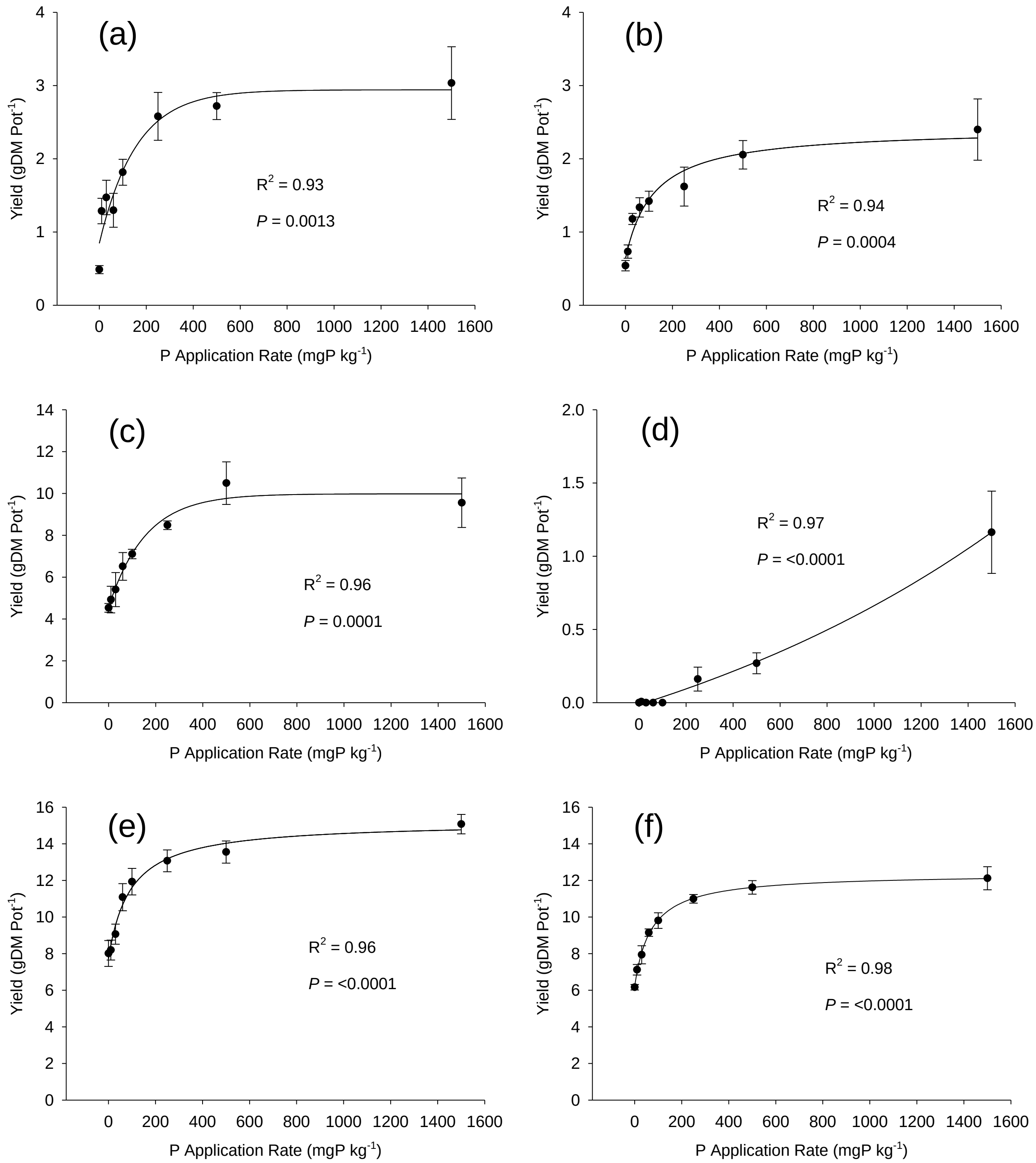

Figure 1: Total accumulated shoot dry matter (DM) yield response of pasture legume species (a) arrowleaf clover (*T. Vesiculosum L.*), (b) balansa clover (*T. michelianum*), (c) Caucasian clover (*T. ambiguum*), (d) gland clover (*T. glanduliferum*), (e) lotus (*L. pedunculatus*), (f) lucerne (*M. sativa*) to increasing levels of soil phosphorus (8 levels of P; ranging from 0 to 1500 mg P kg^{-1}soil), grown in 4 mm-sieved NZ high country soil. Data are mean values ± SEM (n=4), with P and R^2 values for fitted curve showing data trend.

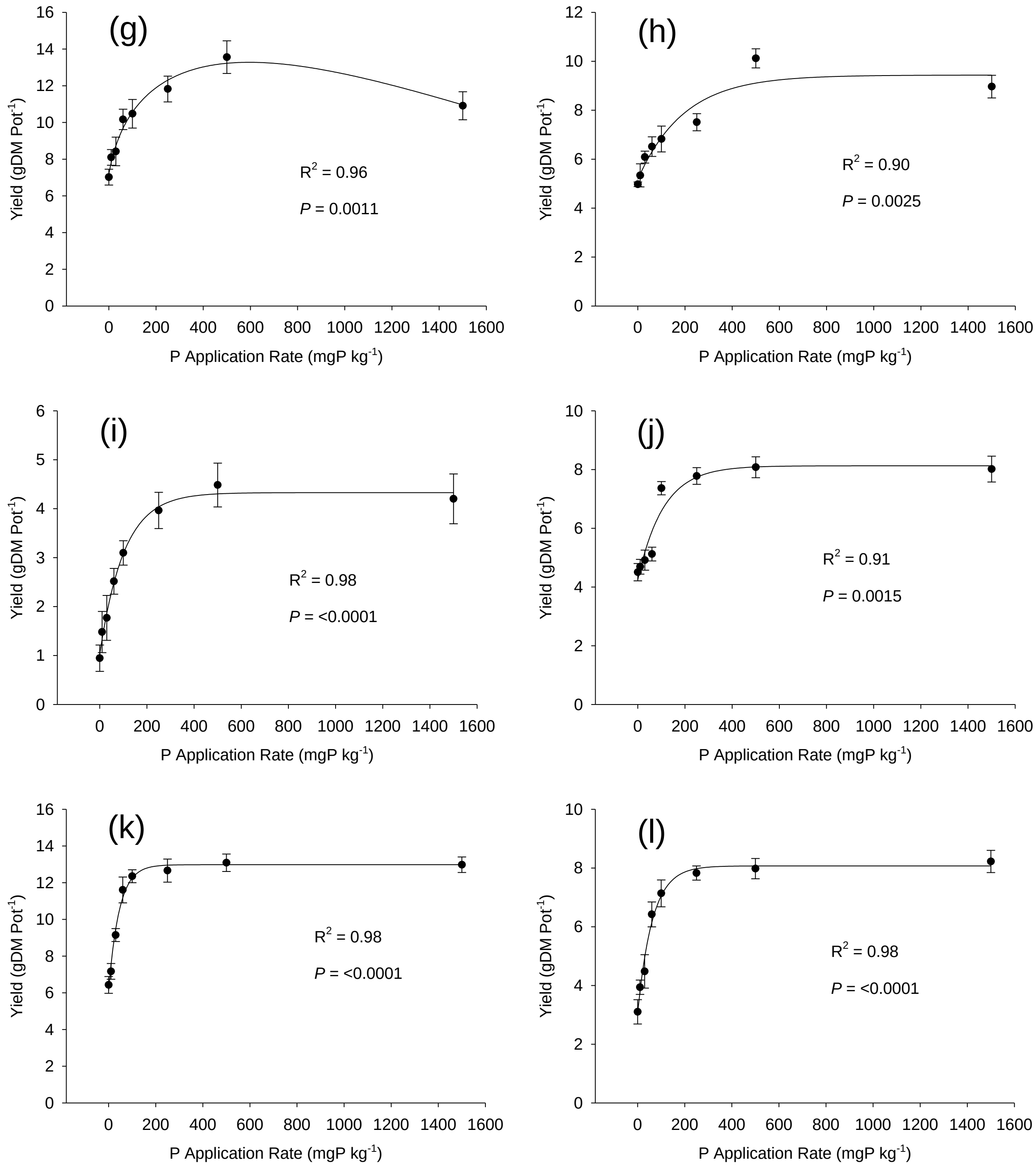

Figure 1 (Cont.): Total accumulated shoot dry matter (DM) yield response of pasture legume species (g) Persian clover (*T resupinatum*), (h) falcata lucerne (*M. falcata*), (i) subterranean clover (*T. subterranium*), (j) strawberry clover (*T. fragiferum*), (k) tagasaste (*C. proliferus*), (l) white clover (*T. Repens*) to increasing levels of soil phosphorus (8 levels of P; ranging from 0 to 1500 mg P kg^{-1}soil), grown in 4 mm-sieved NZ high country soil. Data are mean values ± SEM (*n*=4), with *P* and R^2 values for fitted curve showing data trend.

Table 1: Rate of P application, equivalent Olsen P and shoot P concentration at which 97% of maximum yield was observed for each pasture legume species.

Species	P rate (mgP kg^{-1} soil)	Olsen P (mg L^{-1})	97% Maximum Yield (g DM pot^{-1})	Shoot P Concentration (%)
Arrowleaf clover	517	66	2.8	0.28
Balansa clover	888	108	2.2	0.36
Caucasian clover	439	57	9.7	0.32
Gland clover	1467	175	1.1	0.35
Lotus	440	57	14.3	0.31
Lucerne	669	83	11.7	0.29
Persian clover	369	48	12.9	0.25
Russian (falcata) lucerne	536	68	9.1	0.39
Subterranean clover	336	45	4.2	0.26
Strawberry clover	302	41	7.9	0.28
Tagasaste	132	21	12.6	0.23
White clover	202	29	7.8	0.32

Discussion

The annual species yielded ($P < 0.001$) less than the perennial species with the exception of Persian clover due to their shorter growth period, as annual species go to seed, die and re-establish from seed each year. Persian clover had the highest total DM yield of the annual species across all phosphorus treatments (12.9 g DM pot^{-1}), while the other species were much lower yielding, producing less than 4.2 g DM pot^{-1} under optimum P conditions (16,407 - 1601 kg DM ha^{-1}) (Table 1). All annual species ranked in the same order across all P treatments.

Arrowleaf clover had the greatest percent increase in yield with increasing P inputs from the control treatment (0 mg P kg^{-1} soil; Olsen P = 7 mg L^{-1}) with a 524% increase in yield when 1500 mg P kg^{-1} soil (Olsen P =181 mg L^{-1}) was applied, but produced a relatively low yield at 3.0 g DM pot^{-1} at this P rate. Persian clover, the highest yielding annual species had a 93% increase in yield from the control (0 mg P kg soil) at 500 mg P kg $soil^{-1}$ (Olsen P = 58 mg L^{-1}), and yielded 13.6 g DM pot^{-1}. The P rate at which maximum yield was achieved, and no more response was evident differed between annual species, illustrated in Figure 1. This indicates that some species have better P utilization than others. This ranged from yield maximum P rates of 335 mg P kg^{-1} (subterranean clover) to 1466 mg P kg^{-1} (gland clover). Species such as arrowleaf, balansa and gland clover only yielded once or twice before flowering and therefore dying. Gland clover failed to yield at below 250 mg P kg^{-1} (Olsen P = 31 mg L^{-1}), and was very low yielding once it did produce herbage, with a maximum yield at just 0.3 g DM pot^{-1}. While it emerged with the other species, the seedlings remained very small throughout the experiment. The reasons for this are unknown, as other studies have shown it is tolerant of water logging and produced yields at a pH of 5.3 (Hayes et al. 2008b). This may limit the comparisons that can be made for some of these annual species. However even with limited data, strong relationships between P application rate and yield were apparent for these species ($P < 0.001$). Further experiments are required to confirm the relationships of some of these species in particular gland clover.

The perennial species yielded more ($P > 0.001$) than the annual species with the exception of Persian clover (12.9 g DM pot^{-1}) due to the longer growth period of the perennial species. Lotus had the highest mean yield across all P treatments of the species (14.3 g DM pot^{-1}). The other species were lower yielding, in the order of tagasaste > lucerne > Caucasian clover > falcata lucerne > strawberry clover > white clover (13.1, 12.1, 9.6, 9.0, 8.1, 8.2 g DM pot^{-1}) equivalent to 18168 – 9961 kg DM ha^{-1} 42 $weeks^{-1}$. Overall, white clover was the lowest yielding species from the perennials, which confirms its lack of suitability to these low fertility environments, even when soil moisture was non-limiting in this experiment.

The percent increases in yield between the control (0 mg P kg $soil^{-1}$) and maximum yield with P inputs, were much lower for the perennial species than that of the annual species. These ranged from 165% (white clover, 1500 mg P kg $soil^{-1}$) to 78% (strawberry clover, 1500 mg P kg $soil^{-1}$) with a mean increase in total DM of 103% across all perennial species between the control (0 mg kg $soil^{-1}$) and maximum P treatment (1500 mg kg $soil^{-1}$). The P rate at which maximum yield was achieved, and yield response decreased differed among perennial species. This ranged from 132 mg P kg^{-1} (Olsen P = 21) for tagasaste to 669 mg P kg^{-1} (Olsen P = 83 mg L^{-1}) for lucerne.

Caradus (1980) carried out a similar experiment, investigating the effect of P on ‘Treeline’ Caucasian clover, ‘Palestine’ strawberry clover, ‘Maku’ lotus, ‘Woogenallup’ subterranean clover and ‘Huia’ white clover. Comparable phosphorus rates were used (300 and 2000 mg P kg $soil^{-1}$) in pots of naturally P deficient soil (Stratford coarse sandy loam) over 24 weeks, however only the harvest three data were presented (6 weeks growth). Caucasian clover yielded 0.3 and 0.8 g DM pot^{-1}, strawberry clover yielded 1.2 and 1.7 g DM pot^{-1}, lotus yielded 3.8 and 6.0 g DM pot^{-1}, subterranean clover yielded 3.6 and 7.0 g DM pot^{-1} and white clover yielded 1.8 and 5.2 g DM pot^{-1} at 300 and 2000 mg P kg $soil^{-1}$. These yields were significantly less than those found in this experiment. This was because they only had one plant per pot, compared with five in this experiment. Also the plants were only grown over six weeks compared with 42 weeks in this experiment. Subterranean clover out-yielded lotus in their experiment which contrasts our result, but this was most likely due to subterranean clover being an annual species. This meant that in our trial it got to the end of its life cycle compared with lotus which was still actively growing many weeks later. The soil used in that experiment also had a very high phosphorus retention capacity. Caradus (1980) also found that lotus yield was less affected by P inputs in terms of an increase in yield, with just a 36% increase in yield, compared with a 46% increase in this experiment.

Caradus et al. (1995) found that there were no significant increases in yield between 400 and 500 mg P kg $soil^{-1}$, while the yield increased from 0 to 400 mg P kg $soil^{-1}$ for 119 different cultivars of white clover. This contrasts the results of this experiment where ‘nomad’ white clover continued to increase in yield up to 1500 mg P kg $soil^{-1}$. This may have been due to ‘nomad’ white clover responding to a higher P status of the soil than the mean of the cultivars.

Hart and Jessop (1984) found that 'Maku' lotus out yielded white clover across all P application rates (50, 100, 250, 500, 1000 and 2000 mg P kg soil^{-1} in the form of H_3PO_4) which agrees with our findings. This is likely due to lotus having superior root growth compared with white clover and therefore greater opportunity to infiltrate the soil volume and take up P (Scott & Lowther 1980).

Dodd and Orr (1995) found similar results, in a soil core experiment looking at the phosphorus response from 18 annual herbaceous legume species under low soil pH (5.4) with two rates of P fertility (Olsen P = 10 and 24 mg L^{-1}). They found that subterranean clover, balansa clover and arrowleaf clover all yielded more with improved phosphorus status in the soil.

The magnitude of the response differed among species in this experiment, with gland clover giving the greatest response of all, yielding 1.2 g DM pot^{-1} compared with 0 g DM pot^{-1} with no P input (Figure 1). This was followed by arrowleaf clover, balansa clover and subterranean clover gave the greatest response from control (0 mg P kg^{-1}) to 1500 mg P kg^{-1} of 524%, 344% and 344% respectively. Of the perennial species, tagasaste and Caucasian clover gave the best response to added P (1500 mg P pot^{-1}) increasing in yield by 165% and 111%. These species gave the greatest response to high levels of P, and therefore if these species are used, a higher P status of the soil may be justified, although tagasaste still performed well under low P conditions.

Phosphorus supply was the main driver that increased yields across all species. Yield increased sharply in all annual and perennial species with increasing inputs of P to the system, with the exception of gland clover. The biological optimum yield (97%) was reached at different P rates for different species (Table 1). Of the annual species subterranean clover and Persian clover reached their biological optimum yields at much lower P rates (336 and 369 mg P kg^{-1} ; Olsen P 45 and 48 mg L^{-1}) compared with gland and balansa clovers (1467 and 888 mg P kg^{-1}). Of the perennial species, tagasaste, white clover and strawberry clover achieved biological optimum yields at much lower P rates (132, 202 and 302 mg P kg^{-1}) than for lucerne and falcata lucerne (669 and 536 mg P kg^{-1}). Beyond these P rates, yield did not increase, suggesting that factors other than soil P availability began to limit yield. Of the annual species the Persian clover was the highest yielding with no P input at 7.0 g DM pot^{-1} which was higher ($P < 0.001$) than the other annual species which all yielded less than 1.0 g pot-1 under these conditions. Lotus, tagasaste and lucerne were the highest yielding of the perennial species with no phosphorus inputs, yielding 8.0, 6.2 and 6.1 g DM pot^{-1}, more ($P < 0.001$) than the other perennial species under these conditions. This result indicates that Persian clover, lotus, tagasaste and lucerne are able to be very productive, even in low P fertility high country soils, when compared to the other species in this experiment.

Although a growth response to P was expected, this has not been documented in scientific literature for many of the species examined in this experiment. Further, more information on optimum soil P levels for many pasture legumes does not exist. Therefore much of the data presented here is new and valuable information for species such as tagasaste, falcata lucerne and gland clover.

Conclusions

The objective of this study was to determine the effects of P addition on the growth and nutrient uptake of 12 novel legume species on an acidic high country soil from the Lees

Valley in North Canterbury. This experiment has clearly identified the effects of these treatments on the yield and nutrient uptake of the 12 legume species in a pot trial under glasshouse conditions.

Phosphorus inputs increased ($P < 0.001$) the yields of all annual and perennial species. The highest yielding annual species was Persian clover at both low and high P inputs and had a 97% of maximum yield of 12.9 g DM pot^{-1} at 369 mg P kg^{-1} soil (Olsen P = 48 mg L^{-1}). All other annual species yielded less ($P < 0.001$) at their respective optimum P rates. The highest yielding perennial species was lotus at both low and high phosphorus rates with a 97% of maximum yield of 14.3 g DM pot^{-1} at 439 mg P kg^{-1} soil (Olsen P = 56 mg L^{-1}). Tagasaste and lucerne were also high yielding, while white and strawberry clovers were the lowest yielding perennial species. This increase in yield was driven by increasing P availability in the soil, and therefore increased P uptake by the plants. The P rate at which the maximum yield was achieved varied greatly between species, but the maximum yield of the species must be taken into account when interpreting these values.

This experiment has identified the optimum soil phosphorus conditions for these species, of which for many this is new and valuable information. The suitability of these species must be considered in terms of climatic and physical factors experienced in the field environment, including grazing and mixed sward competition effects. The results of this glasshouse experiment must therefore be interpreted with these factors in mind.

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