Yield and phosphorus use efficiency of irrigated lucerne grown in a low Olsen P soil

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Abstract

Phosphorus (P) is a key nutrient recommended for optimal nitrogen fixation by legumes in New Zealand pastoral systems. However, few field studies have examined the response of legume monocultures to soil P levels. This research aimed to quantify how phosphorus affects lucerne growth and development in an irrigated cut and carry system with a starting Olsen P of 9 mg/L. A randomized complete block design with five superphosphate treatments (0, 50, 100, 200, 400 kg/ha/y) and four replicates was established within a stand of 'Kaituna' lucerne. All herbage was cut-and-carried to ensure no nutrient transfer or return from livestock. Lucerne stem height and annual yields (12000–20000 kg DM/ha) were not different among treatments over four years even when the Olsen P in the Control declined to ~3 mg/L in the top 150 mm. Herbage phosphorus use efficiency was consistently highest in the 50 kg superphosphate/ha treatment with eight times the quantity of applied phosphorus extracted from the soil profile. The 400 kg superphosphate/ha treatment was the only P application rate that was sufficient to fully replace P removed in herbage. These findings suggest lucerne growth was not limited at Olsen P levels below current recommendations, which suggests lucerne was acquiring P below the measured depth and/or accessing P not measured by the Olsen P test.

Keywords: alfalfa, *Medicago sativa* L, phenological development

Introduction

Legumes play a critical role in New Zealand pastoral systems by providing nitrogen inputs through bacterial nitrogen fixation, and high quality feed for ruminants (Moir et al. 2016). Lucerne (alfalfa; *Medicago sativa* L.) is a forage legume typically grown as a monoculture and used to increase animal performance in dryland systems (Moot et al. 2016; Moot et al. 2024), where nutrient costs are primarily from phosphorus, potassium, and sulphur (Morton et al. 2001). However, most pastoral research on P has focused on pasture mixes, where legumes compete with companion grasses. Grasses have fibrous root systems that result in them being more efficient "explorers" for non-mobile nutrients such as phosphorus (Caradus 1980). The consequence is that legume populations decline in low P environments, so fertiliser applications must be sufficient to meet the grass demand before the legume needs can be met (Olykan et al. 2024).

Risk and Smith (1992) examined the phosphorus fertiliser requirements of lucerne grown for hay in Southland and concluded Olsen P values below 9 mg/L in the top 150 mm were deficient, with relative yields declining from 95% to 75%. However this study was conducted on a shallow Oreti silt loam with a rooting depth of 450 mm, which may not represent lucerne grown in deeper soils. In contrast, Smith et al. (2014) found no response to superphosphate application rates from 0 – 120 kg P/ha for irrigated lucerne in Central Otago, where relative yields remained at 90% at an Olsen P of 5 mg/L. Similarly Jones et al. (2025) also reported no response of grazed dryland lucerne to Olsen P levels as low as ~10 mg/L, with shoot biomass yields reaching ~19 t/DM/ha.

Olsen P has been the most commonly used soil test for plant available P in New Zealand pastoral systems since the mid 1970's (Sinclair et al. 1997). Sinclair et al. (1997) ran the most detailed evaluation on the Olsen P test for pastoral soils in New Zealand. It was determined that Olsen P was unable to predict relative yield at any site ($R^2 = 0.27$) unless the Olsen P results exceeded 20 mg/L, with large variability between sites. They concluded Olsen P should only be used to predict the probability of a specified relative yield not being achieved without fertiliser application.

The application of P represents a significant cost to farmers and excess P application can have negative environmental outcomes (Ruttenberg 2003). Therefore, the current field study was initiated to examine the yield response of an irrigated lucerne monoculture grown on a deep silt loam soil when different rates of superphosphate were applied over four years.

Materials and Methods

Site Information

The experiment was located in Iversen Field, at the Lincoln University Field Research Centre, Canterbury,

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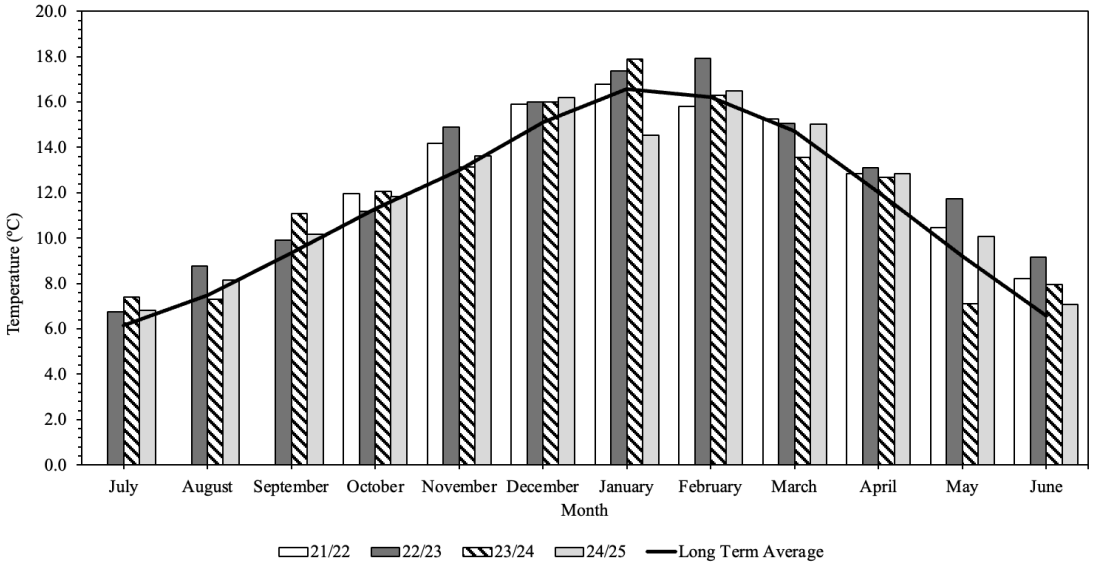


Figure 1 Mean monthly air temperature (°C) from the 21/22, 22/23, 23/24, and 24/25 growing seasons, recorded at the Broadfields meteorological station (Agent Number 17603). The black line is the long term mean for the period of 1995 to 2025.

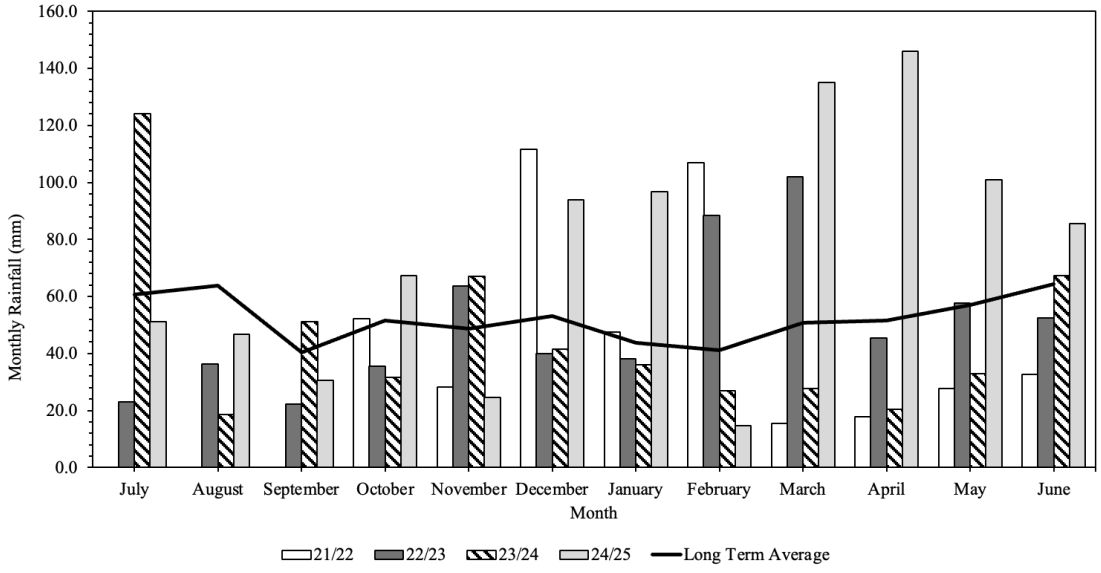


Figure 2 Accumulated monthly rainfall (mm) from the 21/22, 22/23, 23/24, and 24/25 growing seasons, recorded at the Broadfields meteorological station (Agent Number 17603). The black line is the long term mean for the period of 1995 to 2025.

New Zealand (-43.649, 172.465, 9 m a.s.l.). The soil type is an imperfectly to moderately well-drained Wakanui silt loam (Aquic Haplustept, USDA Soil Taxonomy), classified as a mottled immature pallic soil in the New Zealand soil classification (Cox 1978). Wakanui silt loams typically have 0.3 m of topsoil overlying silt loam dominant horizons to a depth of 3.5 m (Cox 1978). Webb (2003) reported that the plant available water-holding capacity for a Wakanui silt loam is 150 mm/m. Irrigation was applied to maintain a soil moisture deficit above 180 mm (50% of PAWC to 2.3 m).

Prior to sowing the paddock was in a perennial ryegrass white clover mix pasture. This was sprayed out using glyphosate 450 at an application rate of 4 l/ha (450 g/l a.i glyphosate). The seedbed preparation consisted of ploughing, then a Dutch harrow and heavy rolling. The experiment was conventionally drilled with a Flexiseeder 14 coulter plot drill with 'Grasslands Kaituna' lucerne on the 21st of October 2021. It was

Table 1 Soil test results sampled from paddock Iversen 5 located at Lincoln University, Canterbury at a depth of 150 mm.

Date	Superphosphate rate (kg/ha)	pH (H_2O)	Olsen P mg/L	Ca	Mg	K	SO_4^{2-} mg/kg
				---------- me/100 g ----------			
22/03/2021	Pre-sowing	6.1	9	5.0	1.21	0.41	6
01/11/2022	0	5.8	5	6.8	0.79	0.17	2
	50	5.9	5	6.9	0.83	0.17	2
	100	6.0	5	7.2	0.83	0.18	3
	200	5.9	6	7.2	0.8	0.25	3
	400	5.9	8	6.6	0.77	0.18	3
03/05/2023	0	5.9	5	7.3	0.9	0.22	7
	50	5.9	3	6.7	0.86	0.19	9
	100	5.9	4	7.5	0.93	0.20	9
	200	5.9	6	7.5	0.93	0.20	10
	400	5.8	6	7.0	0.89	0.19	12
22/03/2024	0	5.9	5	7.4	0.84	0.31	9
	50	6.1	5	8.1	0.93	0.33	12
	100	6.0	5	7.5	0.95	0.32	12
	200	5.9	6	8.2	0.93	0.25	12
	400	5.9	8	7.9	0.92	0.39	9
27/03/2025	0	6.1	2	7.3	1.05	0.36	8
	50	6.0	3	7.1	0.99	0.32	10
	100	6.0	4	7.2	1.01	0.41	9
	200	5.9	6	7.5	0.92	0.39	11
	400	6.1	9	8.6	1.1	0.37	12

All statistical analysis was performed in R studio (Version 2024.12.0+369). A one-way analysis of variance was performed to compare means of each variable for each of the years. A Fishers protected LSD analysis was used to separate the means. Linear regressions were calculated for annual yield against soil Olsen P values.

sown at 12 kg coated seed/ha (Superstrike® treated) at a depth of 15 mm. The experiment was a randomised complete block design, with five treatments (0, 50, 100, 200, or 400 kg Superphosphate/ha), and four replicates. Superphosphate (9% P, 11% S, and 20% C) was applied annually in spring, with additional sulphur and calcium supplied in non-limiting amounts so that phosphorus was the only nutrient below optimal levels. The plots were 10 x 12.6 m, with two 3 m buffer zones between Reps 1 and 2, and Reps 3 and 4, and a 6 m buffer in the centre of the experiment to faciliate irrigation application and mechanical herbage removal.

Measurements

Climate data including air temperature, rainfall, and Penman potential evapotranspiration were obtained from the local Broadfield weather station 17603 (~2 km from the site), on the NIWA Datahub climate database. These are shown in relation to the long-term means during the experimental period (Figure 1, Figure 2). Total rainfall after establishment was 439 mm in 21/22, 810 mm in 22/23, 545 mm in 23/34 and 893 mm in 24/25, compared to the long term mean of 626 mm.

Shoot yield was measured at 14 day intervals after grazing by cutting a 0.2 m^2 quadrat in each plot to crown level (~1 cm above ground level). Samples were oven dried at 65 °C until constant weight and weighed. Stem height was measured with a 1 m ruler at weekly intervals on five marked plants per plot from the base of the stem to the top leaves when the stem was held up straight. Number of nodes was counted weekly on the same marked stems. The number of senesced nodes were assessed on the same stems. Herbage phosphorus was measured using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES). The bulk samples from the herbage dry matter were ground up (using a Ultra Centrifugal Mill ZM 200; Retsch, Germany) after drying and then used for the ICP-OES test. For this the sample is converted into a soluble form using HNO_3 for acid digestion. It is then introduced to argon plasma

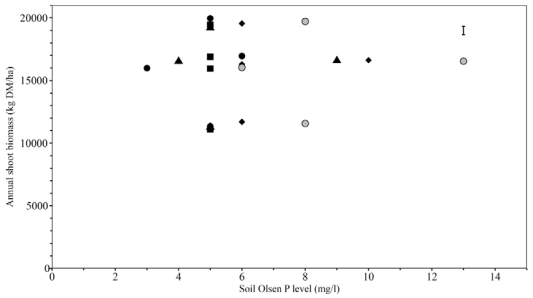


Figure 3 Annual shoot biomass (kg DM/ha) against soil Olsen P (sampled a depth of 150 mm) for lucerne in the 21/22, 22/23, 23/24, and 24/25 growing seasons with superphosphate applied at rates of 0 (■), 50 (●), 100 (▲), 200 (◆), or 400 (●) kg/ha annually in each of the individual plots at Lincoln University, Canterbury, New Zealand. The error bar is the SEM for comparing annual shoot biomass (kg DM/ha) against soil Olsen P.

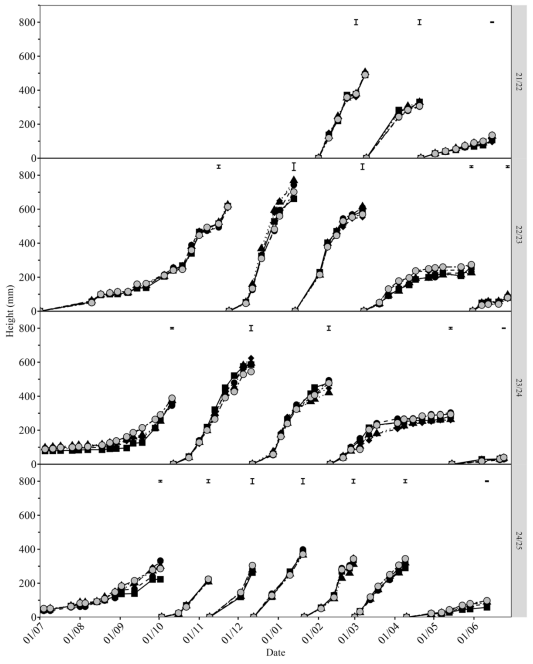


Figure 4 Stem height (mm) over time for seedling lucerne crops after sowing on 21/10/2021 and subsequent regrowth crops in the 21/22, 22/23, 23/24, and 24/25 growing seasons with superphosphate applied at 0 (■), 50 (●), 100 (▲), 200 (◆), or 400 (●) kg/ha at Lincoln University, Canterbury, New Zealand. The error bar is the SEM for comparing stem height (mm) on the final observation date of each rotation.

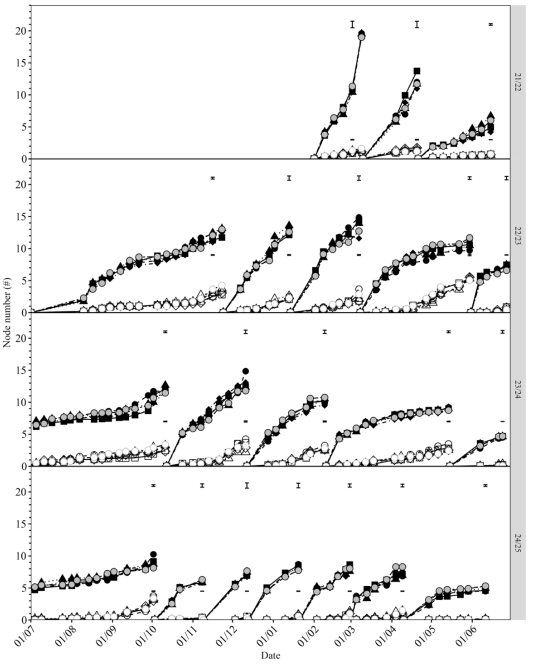


Figure 5 Total number of mainstem nodes (filled symbols) and number of senesced mainstem nodes (open symbols) over time for regrowth lucerne crops grown in the 21/22, 22/23, 23/24, and 24/25 growing seasons with superphosphate applied at rates of 0 (■), 50 (●), 100 (▲), 200 (◆), or 400 (●) kg/ha annually at Lincoln University, Canterbury, New Zealand. The error bar is the SEM for comparing the final number of nodes for each rotation.

where atoms emit light at element specific wavelengths. This emitted light is then used to quantify phosphorus levels. Phosphorus use efficiency was calculated as the kg of P removed in the herbage/the kg of P applied. Olsen P soil tests (Olsen 1954) were conducted by Hill Laboratories in Christchurch, New Zealand (Table 1). Ten soil cores (0-150 mm) were taken at random locations in each plot and bulked for each of the five treatments prior to testing.

Results

There was no difference in the total annual shoot biomass (Figure 2) with 12000±532 kg DM/ha in 21/22 ($p = 0.72$), 17000±646 kg DM/ha in 22/23 ($p = 0.80$), 18000±729 kg DM/ha in 23/24 ($p = 0.66$) and 20000±511 kg DM/ha in 24/25 ($p = 0.89$). There was no relationship between Olsen P and annual shoot biomass (Figure 1; $R^2 = 0.004$).

There was no difference ($p > 0.05$) in stem height at any observation date over the four growing seasons (Figure 2).

At no time was there any difference in the number

Table 2 Herbage phosphorus use efficiency (PUE; kg P/ha removed/kg P/ha applied) from the 21/22, 22/23, 23/24, and 24/25 growing seasons at Lincoln University, Canterbury, New Zealand.

	Superphosphate rate (kg/ha)						
Growth Season	**0**	**50**	**100**	**200**	**400**	**p value**	**SEM**
21/22	-	6.89 $_a$	2.89 $_b$	1.78 $_c$	0.83 $_c$	0.002	0.40
22/23	-	7.33 $_a$	3.56 $_b$	1.83 $_c$	0.86 $_c$	0.005	0.50
23/24	-	7.33 $_a$	3.22 $_b$	1.94 $_c$	0.86 $_c$	0.008	0.45
24/25	-	11.3 $_a$	5.22 $_b$	2.83 $_c$	1.42 $_c$	0.001	0.60
Total PUE		8.22	3.72	2.10	0.99		

Note: - indicates not calculated. Means followed by the same letter are not different at the α=0.05 level.

of mainstem nodes produced among treatments (Figure 3; $p > 0.05$). There was also no difference in the rate of leaf senescence at any observation date of the four growth seasons ($p > 0.05$).

Annually, herbage phosphorus use efficiency (Table 2) was consistently highest in the 50 kg superphosphate/ha treatment, and then the 100 kg/ha treatment. There was no difference in PUE of the 200 and 400 kg/ha superphosphate rates in any growth season which averaged at 2.10 and 0.99. PUE of the 50 kg/ha treatment ranged from 6.89 (21/22) to 11.3 kg P removed/kg P applied per hectare (24/25) while the 100 kg superphosphate/ha treatment produced 2.89 (21/22) to 5.22 kg P removed/kg P applied per hectare (24/25). The 200 and 400 kg/ha superphosphate rates had a PUE of 1.31±0.40 in 21/22 ($p < 0.01$), 1.35±0.50 in 22/23 ($p < 0.01$), 1.40±0.45 in 23/24 ($p < 0.01$), and 2.13±0.60 kg P removed/kg P applied per hectare in 24/25 ($p < 0.01$).

Discussion

Our results showed no relationship ($R^2 = 0.004$) between annual shoot biomass and soil Olsen P, which ranged from 2-13 mg/L (Figure 1). This aligns with previous reports of a lack of relationship with relative yield expected when Olsen P levels are < 20 mg/L (Sinclair et al., 1997). Regardless, the annual shoot biomass was 12000 (21/22), 17000 (22/23), 18000 (23/24), and 20000 kg DM/ha (24/25), which were consistent with previous results from this environment (e.g. Mills et al. (2008), Brown et al. (2005)) and suggest that P was not restricting shoot biomass production at any stage over the four years of investigation. At sowing, the initial Olsen P (9 mg/L) was below recommended levels of 20 mg/L, for growing lucerne (Roberts et al. 1994).

The lack of difference in stem height (Figure 2) was consistent with the yield results and suggests that neither the rate of node appearance (Figure 3) nor the rate of stem extension (Figure 2) were impacted by the P treatments. Together these results suggest neither the growth nor the development of the lucerne crops was affected by soil P levels. The implication is that the Olsen P of 2 mg/L in the 0 kg superphosphate/ha treatment was sufficient to maintain a high lucerne yield at this site after four years. This value is much lower than the Olsen P requirement of 9 mg/L reported by Smith et al. (2014) for 95% of maximum yield. They showed that, in the top 150 mm soil layer, an Olsen P of 9 mg/L was required to reach 95% of maximum yield. Risk and Smith (1992) examined the phosphorus fertiliser requirements of lucerne and reported a relative yield decrease from 95% to 75% as Olsen P declined from 13 to 7 mg/L at a depth of 75 mm. The greater depth used in the current study may have diluted the measured P values compared with previous research because P is most commonly surface applied and immobile. Thus, sampling depth needs to be considered when evaluating Olsen P recommendations.

The current recommendations for P applications to lucerne stands in a cut and carry system are 20-30 kg P/ha/y (Morton et al. 2020). These are higher under cutting than grazing due to a lack of P return through animal excretions. In the current study superphosphate treatments applied the equivalent of 0 to 144 kg P/ha. The total amount of P removed in the herbage remained consistent at ~142 kg/ha irrespective of the amount of P applied. This highlights that only the 400 kg superphosphate/ha treatment (144 kg/P/ha) was sufficient to replace the total quantity of P removed and with the decline in Olsen P in the top 150 mm soil layer from 5 to 3 mg/L in the treatment with no P applied. This suggests that in the treatment with no P applied, ~122 kg P/ha was mined from the soil to meet plant demand. The implication is that the P was sourced from existing P pools that were not recognised by the soil test.

These results potentially have substantial financial implications for farmers. For example, current maintenance applications using superphosphate equate to application rates of ~250 kg superphosphate/ha/yr at a cost of ~$230+GST/ha (as of 01/10/2026). In this soil the lucerne was able to produce ~19500 kg DM/

ha/yr at an Olsen P of 3 mg/L (Figure 1). If this results is repeated more broadly, it suggests farmers may be able to reduce their annual superphosphate application rates in lucerne monocultures. However, this may only be appropriate where paddocks remain in long-term lucerne, as subsequent pasture or cropping phases in the rotation are likely to require higher Olsen P concentrations to meet their phosphorus requirements. The results suggest that lucerne may be able to mine subsoil P, but the duration of this buffering effect before yields decline would depend on the soil type, subsoil P reserves, and the rate of removal of P in the herbage.

Olsen P values in this experiment ranged from 3 – 13 mg/L with lucerne yields ranging from 11400 to 19500 kg DM/ha over the four years. This suggests that the Olsen P of 3 mg/L in the top 150 mm was sufficient at this site but does not account for variation across other soil types and depths. The addition of 144 kg P/ha in the 400 kg superphosphate/ha treatment should have raised the initial Olsen P at a 150 mm sampling depth from 9 mg/L (Table 1) to ~33 mg/L (Roberts et al. 1994), but Olsen P in the 400 kg superphosphate/ha treatment stayed constant at 9 mg/L. The plants removed an average of ~137 kg P/ha across the treatments, which combined with the P use efficiency (Table 2) suggests that all of the P applied in the 400 kg superphosphate/ha treatment was taken up. In the Control the ~122 kg P/ha removed in herbage must have been mined from the soil, as there was no P added via fertiliser or animal deposits.

The absence of a relationship between Olsen P and lucerne yield in the current study is consistent with the findings of Sinclair et al. (1997) who ran the most detailed evaluation of Olsen P for pastoral soils in New Zealand. It was reported that Olsen P was a poor predictor ($R^2 = 0.27$) of relative yield when concentrations were below 20 mg/L. In the present experiment the lucerne maintained annual shoot biomass yields up to 19500 kg DM/ha with Olsen P concentrations ranging from 2-13 mg/L, suggesting that the Olsen P test did not adequately reflect plant available P in this environment. This may indicate that lucerne was able to access P from soil pools not measured by the Olsen P test, including subsoil P below the sampling depth.

Conclusions

Lucerne produced 11400 to 19500 kg DM/ha and showed no difference in stem height at Olsen P values ranging from 2 – 13 mg/L, suggesting that an Olsen P of 3 mg/L in the top 150 mm was sufficient if phosphorus was available below this depth. The deep lucerne root system, and root adaptations may have allowed access to subsoil P that is not accounted for in current soil testing recommendations. Further work is required to determine whether these results hold for other soils that lucerne monocultures are grown in.

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