Lucerne (*Medicago sativa* L.) yields were unaffected by phosphorus fertility level under grazing in a dryland farmlet experiment

Lauren JONES*, Annamaria MILLS, Alistair D. BLACK and Derrick J. MOOT

Dryland Pastures Research Group, Faculty of Agriculture and Life Sciences, Lincoln University, Canterbury, New Zealand.

*Lauren.Jones@lincolnuni.ac.nz

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 experiment measured lucerne yield under grazing in the field when grown under two P fertiliser regimes for the first three years of the dryland farmlet experiment at Lincoln University. The 'High' phosphorus treatment aimed for an Olsen P of ~20 compared with ~10 for the 'Low' treatment. Lucerne shoot biomass showed no effect of treatment at any time. This was consistent with no differences observed for lucerne mean daily growth rates and canopy light interception. Additionally linear regression analysis showed no relationship ($R^2 = 0.01$) between soil Olsen P and any of the measured variables. These results suggest that the critical Olsen P may be <10 for dryland lucerne monocultures measured to a soil depth of 75 mm, which is consistent with previous recommendations.

Keywords: alfalfa, *Medicago sativa* L., Olsen P, Regenerative Agriculture Dryland Experiment (RADE).

Introduction

Legumes play a critical role in New Zealand pastoral systems by providing nitrogen (N) inputs through bacterial N fixation, and high quality feed for ruminants (Moir et al. 2016). Phosphorus (P) is an essential macronutrient for legumes because it is a component of many fundamental biochemical reactions such as nitrogen fixation, and photosynthesis (Ruttenberg 2003). Bacterial nitrogen fixation is a phosphorus hungry process as it requires 16 molecules of P to be converted from ATP to ADP for one molecule of N to be reduced to NH_3 (Mitran et al. 2018). Thus, adequate P supply is considered an integral component of legume productivity. In the field, phosphorus is tightly bound to soil particles and can be transported to waterways when erosion events occur leading to an increased risk of eutrophication (McDowell et al. 2009). Phosphorus fertiliser is also a major on-farm expense. Therefore, efficient use of P fertiliser to maximise productivity and minimise potential environmental risks is an important component of farm systems.

Lucerne (*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). As a legume it does not require nitrogen fertiliser, so nutrient costs are from phosphorus, potassium and sulphur (Morton et al. 2001), magnesium and any deficient essential trace elements.. However, most pastoral research on P has focused on pasture mixtures, 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 mixed pastures in low P environments, so fertiliser applications must exceed the grass demand to ensure the legume needs are met (Olykan et al. 2024).

Risk and Smith (1992) examined the phosphorus fertiliser requirements of lucerne grown for hay in Southland. They concluded Olsen P values below 13 mg/l in the top 75 mm were deficient due to a relative yield decrease from 95% to 75% as Olsen P declined from 13 to 7 mg/L. This experiment was on an Oreti stoney silt loam that has a rooting depth of 0.45 m, which may not represent the P availability to lucerne on deeper soils. For example, on a moderately deep sandy loam Smith et al. (2014) found no response to superphosphate application rates from 0 – 120 kg P/ha for irrigated lucerne in Central Otago. Relative yield was still 90% at an Olsen P of 5 mg/l, and reached 95% at an Olsen P of 12 mg/l.

These results, and the focus on environmental concerns in relation to P application and its loss in sediment (McDowell et al. 2009) led to the current study. The aim was to expand the data set available for determining the P requirements of grazed dryland lucerne monocultures grown in the field.

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Materials and Methods

The experiment measured a component of the Regenerative Agriculture Dryland Experiment (RADE) located at the Field Research Centre located at Lincoln University, New Zealand (43°38'54.20" S, 172°27'34.30"E). The soil type is a Templeton silt loam (Udic Haplustoll, USDA Taxonomy) with a variable depth to gravel (0.5-1.5 m) and available water capacity (AWC) of ~140 mm to 0.5 m (Cox 1978). Prior to establishment the soil was cultivated from the 3–9 December 2021. The plots were sown on the 13th of December 2021 with a Flexiseeder® plot drill with 15 cm drill rows. The coated 'Kaituna' lucerne was sown at a target depth of 10 – 15 mm and at a rate of 15 kg/ha. The seedbed was then consolidated with a Cambridge roller.

The experimental area consisted of two treatments in four replicate plots that were 30 x 29 m^2 (0.087 ha) and grazed at an average stocking rate of ~10 ewes/ha. The treatments included "high" and "low" phosphorus soil fertility levels. The "high" treatment had a target to maintain an Olsen P (mg/l) of ~20 and the "low" treatment ~10 (mg/l) (Table 1). To achieve the desired levels superphosphate (9% P 11% S 20% Ca) is applied as required (Table 2). Pregrazing herbage mass depended on available feed throughout the rest of the farmlet but aimed for the lucerne monocultures to be 0.3 m high when possible (Moot et al. 2016). Target grazing residual was when majority of the lucerne leaf and palatable soft stem has been removed (Brown et al. 2006). Data collection started at the first graze event on the 12 March 2022, and finished on the 8 May 2024. This covered the seedling crop and two full growing seasons from 1 June to the 31 May.

Climate data were obtained for the local Broadfield weather station (Agent No. 17603) located ~2 km N of the site from the NIWA Datahub climate database. Air temperature (Figure 1) and rainfall and Penman potential evapotranspiration (Figure 2) for the experimental period are shown in relation to long-term (2003-2023) means. The average annual rainfall at this site is ~600 mm, with a potential evapotranspiration (PET) of ~950 mm. Total rainfall in Year 1 (6-month establishment period) was 327 mm. In Year 2 rainfall totalled 791 mm and in Year 3 it was 531 mm. Penman evapotranspiration in Year 1 was 521 mm (6 month establishment period), while in Year 2 PET totalled 947 mm and Year 3 was 1014 mm. This indicated there was a period of soil moisture deficit which developed in each growth season and was longest in Year 3.

Lucerne shoot biomass was harvested to ground level on a fortnightly basis from three 0.5 m^2 quadrats along the longest axis of the plot using Trade Tested electric sheep shears. Samples were bulked and weighed fresh (FWt), before a ~100 g FWt subsample of lucerne was dried for at least 48 hours at 65°C. Normalised difference vegetation index (NDVI) measurements were taken as an average reading along the longest axis of the plot using a Trimble Greenseeker handheld crop sensor on

Table 1 Soil Olsen P (mg/l) test results sampled to 7.5 cm from lucerne in spring of each growing season. The Olsen P on the 26/01 sampling date was bulked across the 16 plots. Each plot is reported with its target Olsen P treatment of 10 mg/l (L; Low) or 20 mg/l (H; High).

Plot	1 (L)	3 (H)	5 (H)	7 (L)	10 (L)	12 (H)	14 (H)	16 (L)
Establishment (2021)	--10--							
Year 1 (2022)	11	10	12	8	7	14	13	9
Year 2 (2023)	9	12	9	10	7	17	11	7
Year 4 (2024)	8	19	20	7	9	22	23	5

Table 2 Superphosphate fertiliser application rates (9% P) and P applied (kg/ha) to Lincoln University, Canterbury. The total applied is the total fertiliser applied throughout Years 1 – 3 to dryland lucerne plots for high (H; 20 mg/l) or low (L; 10 mg/l) phosphorus treatments.

	Superphosphate (kg/ha)		Phosphorus (kg/ha)	
Date	H	L	H	L
Establishment (2021)	200	0	18	0
Year 1 (2021)	200	0	18	0
Year 1 (2022)	300	44	28	4
Year 3 (2023)	300	25	27	2
Total (kg/ha)	1000	69	91	6

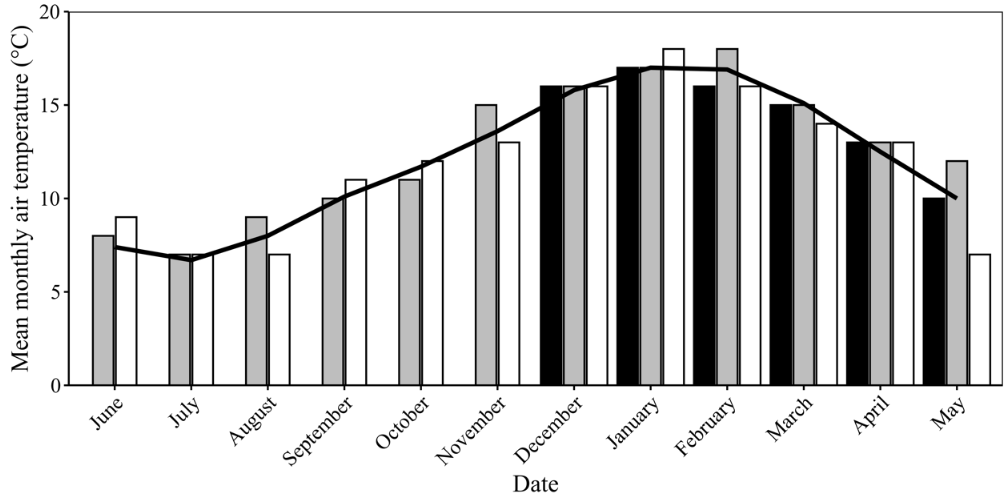

Figure 1 Mean monthly air temperature (°C) from the 21/22 (■), 22/23 (■), and 23/24 (□) growing seasons, recorded at the Broadfield meteorological station (Agent Number 17603). The black line is the long term mean for the period of 2003 to 2023.

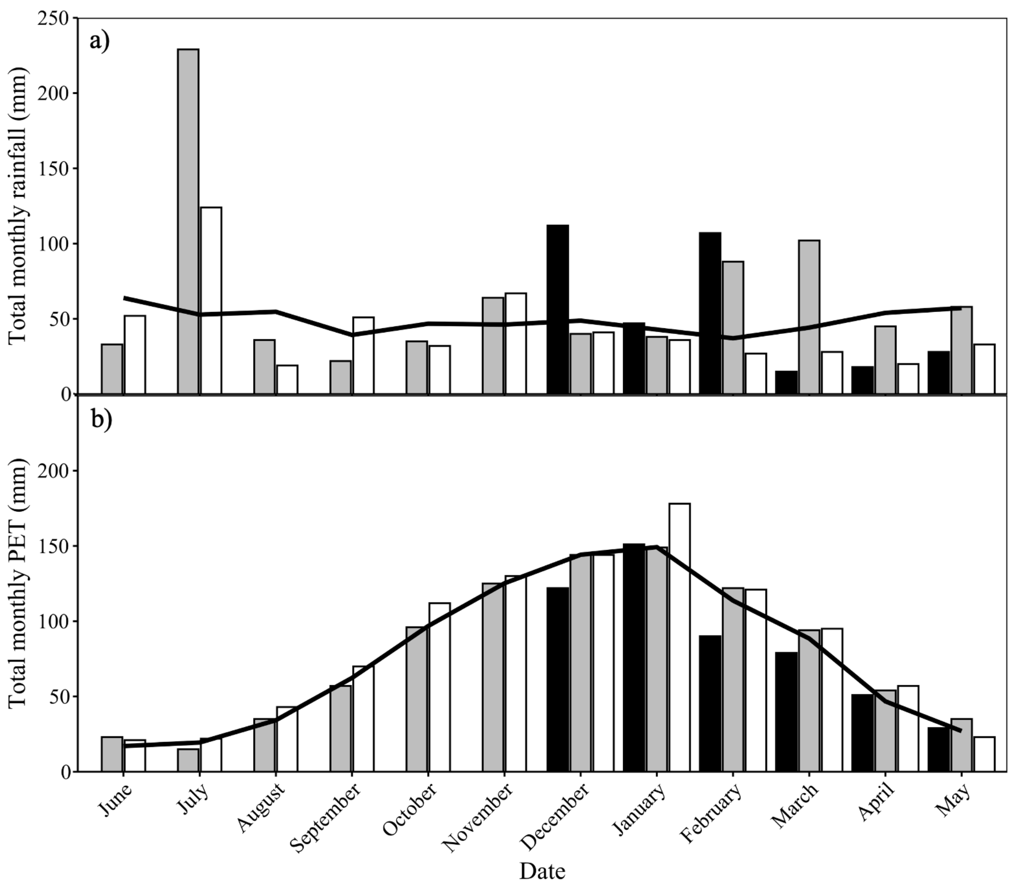

Figure 2 Total monthly rainfall (mm) (a) and Penman evapotranspiration (PET) (mm) (b) from the 21/22 (■), 22/23 (■), and 23/24 (□) growing seasons, recorded at the Broadfield meteorological station (Agent Number 17603). The black line is the long term mean for the period 1993-2023.

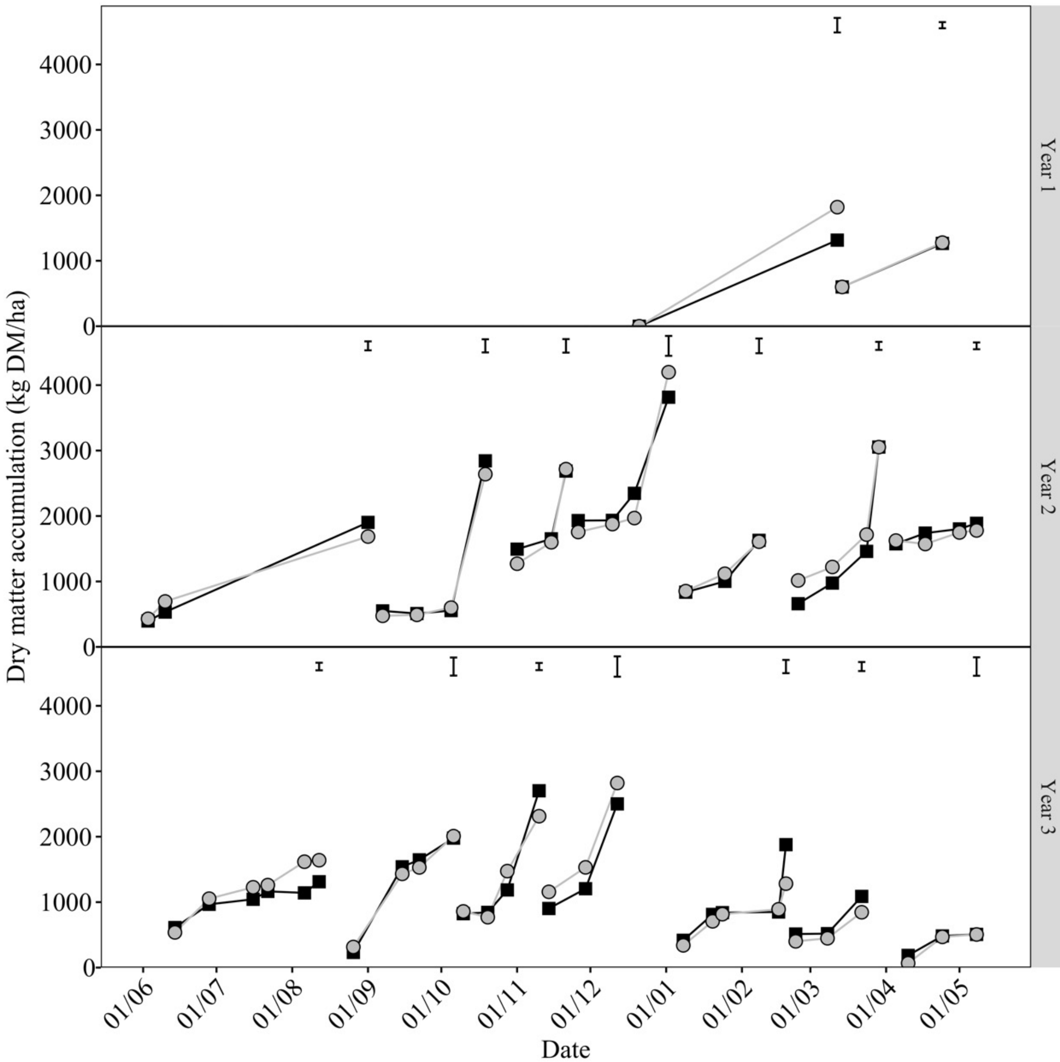

Figure 3 Lucerne biomass over time when grown under high (■) or low (●) phosphorus fertility levels at Lincoln University, Canterbury, New Zealand. Year 1 was the 21/22 growing season, Year 2 was the 22/23 growing season and Year 3 was the 23/24 growing season. The vertical bars are the pooled SEM for each rotation on the final sampling date.

biomass sampling days. NDVI measures the difference between near infrared and red light reflectance as a measure of green groundcover. Values were corrected for bare ground (Oliveira 2015). Water use was calculated using a simple soil water budget of daily rainfall minus Penman potential evapotranspiration. Soil samples were cored to a depth of 75 mm to measure Olsen P (mg/l) to standardise testing across the farmlet.

Statistical analyses used R Studio 4.2.1. A one way analysis of variance determined the effect on shoot biomass, ground cover, and water use efficiency at both phosphorus fertility levels for each sampling date. A linear regression analysis was carried out between water use and Olsen P level on a per plot basis. A linear regression analysis was carried out between annual dry matter accumulation and Olsen P level on a per plot basis. Means are reported with the pooled standard area of the mean.

Results

Lucerne shoot DM yield was not different ($P > 0.05$) between high and low phosphorus treatments on any sampling date (Figure 3) across the three years. Annual lucerne yields also did not differ and averaged 2,800±267 kg DM/ha in Year 1 ($P = 0.31$), 18,700±2400 kg DM/ha ($P = 0.9$) in Year 2, and 10,700±650 kg

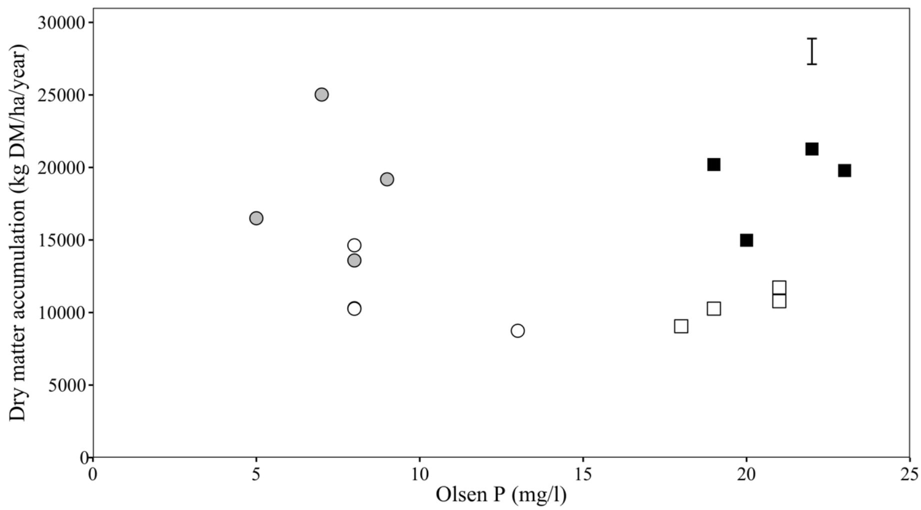

Figure 4 Total annual accumulated lucerne shoot yield (kg DM/ha/yr) against soil Olsen P (mg/l) to a depth of 7.5 cm for individual plots under high (■, □) or low (●,○) phosphorus fertility levels at Lincoln University, Canterbury, New Zealand. The closed symbols are for Year 2 and the open symbols are for Year 3. The vertical bars are the pooled SEM.

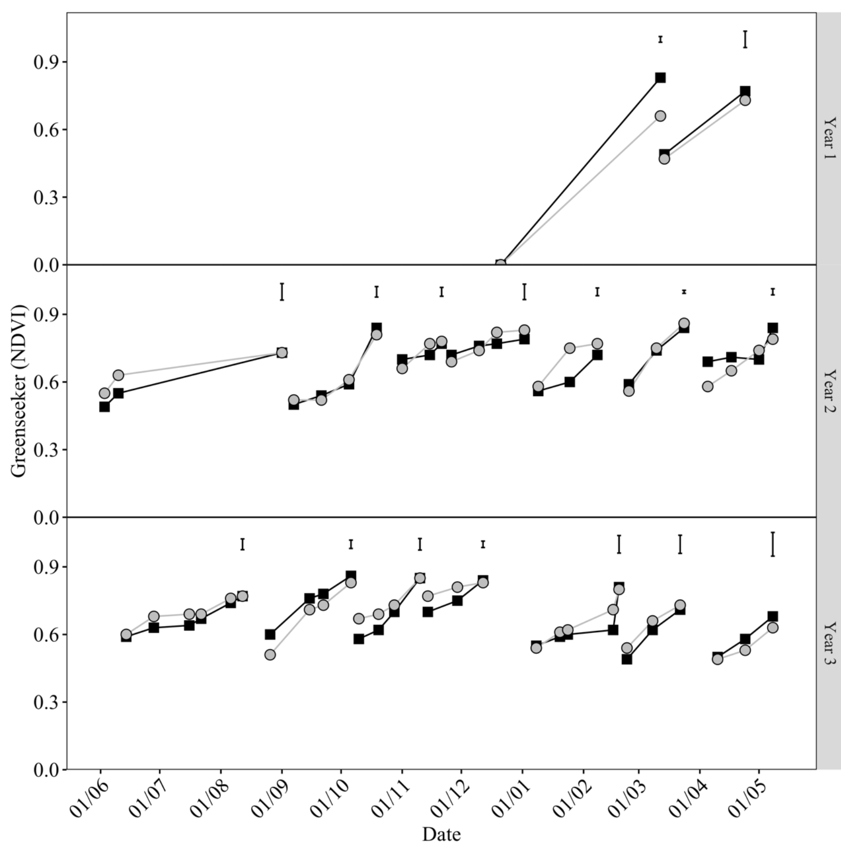

Figure 5 Greenseeker readings (ground cover; NDVI) over time for lucerne under high (■) or low (●) phosphorus fertility levels at Lincoln University, Canterbury, New Zealand. Year 1 was the 21/22 growing season, Year 2 was the 22/23 growing season and Year 3 was the 23/24 growing season The vertical bars are the pooled SEM for each rotation on the final sampling date.

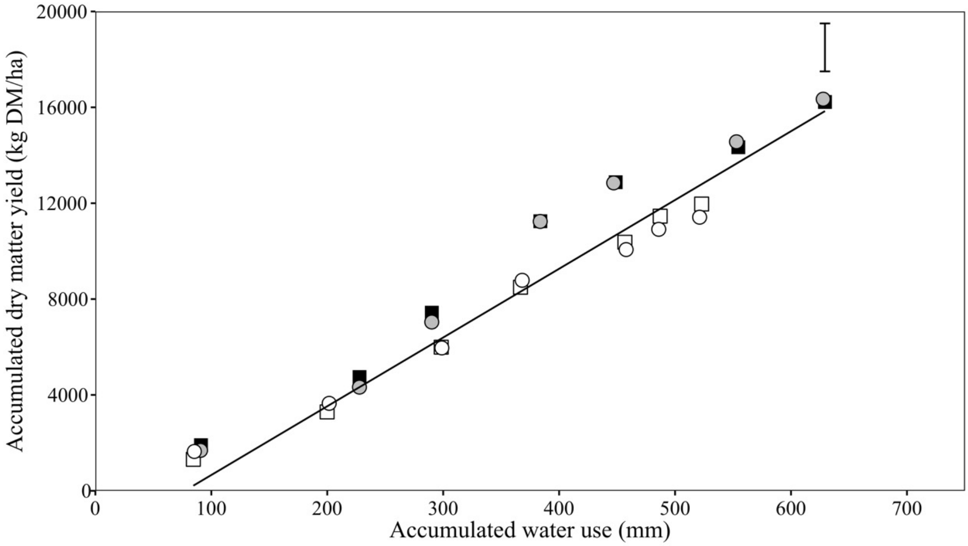

Figure 6 Accumulated dry matter yield (kg DM/ha) against accumulated water use (mm) under low (●) or high (■) phosphorus fertility levels at Lincoln University, Canterbury, New Zealand. The closed symbols are for Year 2 and the open symbols are for Year 3. The form of the regression was y = 28.7x – 2210.3 (R2 = 0.86). The vertical bar is the pooled SEM for total annual shoot yield.

DM/ha in Year 3 ($P = 0.60$). It follows that lucerne growth rates were also not different ($P > 0.05$) between phosphorus fertility treatments for each of the rotations across three growing seasons (Figure 3).

There was no relationship ($R^2 = 0.01$) between annual dry matter accumulation and Olsen P (Figure 2).

Groundcover (NDVI) values did not differ ($P > 0.05$) between high or low phosphorus fertility treatments at any sampling date (Figure 5) across the three growing seasons.

There was a linear relationship between accumulated dry matter (kg DM/ha) and accumulated water use (mm) ($R^2 = 0.87$) but no difference ($P = 0.26$) in water use efficiency (WUE) between the low or high phosphorus treatments in either of the two full growing seasons (Figure 6), which averaged 28±2.74 kg DM/mm.

Discussion

In the establishment year the lucerne produced 2800 kg DM/ha with no significant yield increase due to phosphorus fertiliser application (Figure 4). In Year 1 the target average Olsen P values had not yet been reached for the High P treatment, and were 10 mg/l in the Low P plots, but only 12 mg/l in the High P plots, despite the previous applications of superphosphate (Table 2). Lucerne shoot dry matter yields averaged at 18700 kg DM/ha in Year 2, and 10700 kg DM/ha in Year 3 again with no yield differences (Figure 4). The lower total yield in Year 3 was attributed to the below average 560 mm annual rainfall, in comparison with the 790 mm annual rainfall in Year 2 (Figure 3). This is because the observed dry matter yields (Figure 3) were comparable with those reported by Mills et al. (2008) for dryland lucerne grown at the same site. The consequence was no impact ($P = 0.26$) of Olsen P level on water use efficiency (Figure 6), which averaged ~28 kg DM/mm. This value is at the high end of the values previously reported by Brown et al. (2005), which probably reflects the young age of these stands that had high plant populations and no difference in recovery of the canopy ground cover (NDVI) after each grazing event (Figure 5).

To investigate the data in more detail individual plot data were examined. This showed there was no relationship ($R^2 = 0.00$) between yield and Olsen P (mg/l) (Figure 5). In Year 2 Olsen P in the high fertility plots reached the target and averaged 20 mg/l with an annual yield of 19000 kg DM/ha/year. This was not different to the annual yield in the Low P treatment (18600 kg DM/ha/yr) where the Olsen P level had dropped to 7 mg/l. Year 3 also showed no difference in annual yields with an average of 10500 kg DM/ha at an Olsen P of 20 mg/l and 11000 kg DM/ha at an Olsen P of 9 mg/l. The results showed the lowest Olsen P of 7 mg/l in the top 15 cm was sufficient to maintain a high lucerne yield at this site. This is lower than the Olsen P requirement of 12 mg/l that was reported by Smith et al. (2014) for 95% of maximum yield. They showed that, in the top 75 mm soil layer, an Olsen P of 15 mg/l was required to reach 95% of maximum yield. This suggests that sampling depth should be taken into consideration when reviewing Olsen P recommendations. Risk and Smith (1992) also examined the phosphorus fertiliser requirements of lucerne and concluded Olsen P values below 13 mg/l were deficient due to a relative yield decreased from 95% to 75% as Olsen P declined from 13 to 7 mg/l at a depth of 7.5 cm. This experiment was on an Oreti stoney silt loam that has a rooting depth of 0.45 m, which may not represent the P availability to lucerne on the deeper soils used in the current experiment.

The vast majority of pastoral research on phosphorus has focused on pasture mixes, where legumes compete with grasses for the available phosphorus. Grasses have fibrous root systems that result in them being more efficient "explorers" for non-mobile nutrients such as phosphorus (Caradus 1980). Edmeades et al. (2006) reported that the target Olsen P range for clover based pastures was between 26 – 30 mg/L on sedimentary soils. This is over twice that recommended for lucerne reported (Risk and Smith 1992; Smith et al. 2014), and four times the Olsen P requirement of this experiment. The lower requirements of lucerne may be due to its deeper rooting systems, which allow for greater total uptake than white clover because it explores a larger volume of the soil profile to meet crop demand (Smith et al. 2014). These results suggest legume monocultures may not require the same phosphorus fertiliser requirements as required for legume/grass mixes (Olykan et al. 2024).

Lucerne roots typically exceed 2.3 m in length once established (Sim et al. 2017) in contrast to white clover (*Trifolium repens* L.) root systems, which typically do not exceed 1 m (Nichols et al. 2016). This suggests that soil type, and rooting depth should be taken into account when making decisions around fertiliser application rates. Current maintenance application recommendations are 15 – 25 kg P/ha/yr under grazing or 20 -30 kg P/ha/yr under hay/silage assuming yields of 10000 – 15000 kg DM/ha/yr (Morton 2020). Using superphosphate this would equate to application rates of ~250 kg/ha/yr at a cost of ~$230+GST/ha. With lucerne able to produce ~20000 kg DM/ha/yr at an Olsen P of 7 mg/l, farmers may be able to reduce their annual application rates, or skip annual applications during times of financial deficit in situations where Olsen P values are ~20 mg/l. This provides a financial buffer for farms that have maintained Olsen P levels of 20+.

Further research is required to determine whether these results hold over the full duration of a lucerne stands life cycle and on the range of soil types in which it is grown. If so, then it may be possible to reduce the recommended rates of P required for lucerne crops and, consequently, reduce the amount of P loss when sediment is eroded into water ways, and therefore reduce the risk of eutrophication (McDowell et al. 2009).

Conclusions

In the first three years of this experiment there was no difference in any of the variables measured between the high (Olsen P ~20 mg/l), or low (Olsen P ~10 mg/l) treatments. Lucerne yields averaged at 3000 kg DM/ha in Year 1, 19000 kg DM/ha in Year 2, and 11000 kg DM/ha in Year 3 and a water use efficiency of 28 kg DM/ha/mm. The current recommendations for P fertiliser may need to be reviewed to account for lucerne rooting depth, because much of the current literature only considers Olsen P in the top 15 cm. Further research is required to determine the applicability of this result across soil types.

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