New Zealand Merino Company

Forage establishment and management
in the high country of
New Zealand

June Report 2014

Lincoln University

Professor Derrick Moot	Project Leader
Dr Alistair Black	Lake Heron Station
Dr Jim Moir	Soils
Dr Keith Pollock	Senior Technician
Ms Marie Roux	Technician
Mr Travis Ryan-Salter	PhD Student

Executive Summary

This report focusses on the data for 2013-14 from three experiments at Glenmore Station ('Legumes in low pH areas', 'Sowing rates of lupin', and 'Lucerne and lupin demonstration area'), two experiments at Bog Roy Station ('Legume comparative trial' and 'Legume survivability'), and three experiments at Lake Heron Station ('Undeveloped pasture and Caucasian clover', 'Pot trial', and 'Fertiliser rates'). It also includes an 18 Month Report on Travis Ryan-Salter's PhD progress to date and an appendix of papers to be presented at the New Zealand Grassland's Association 2014 Conference in November this year.

The results of these experiments have again highlighted some key findings across the sites.

Lucerne is still performing well at Bog Roy Station where it has been integrated into the grazing system. At Glenmore Station, however, it is still struggling to perform. This and its growth response to lime, highlights the difficulty in establishing lucerne in high aluminium soils as root development and nodulation are restricted.

Lupin has proven to perform well in the South Island high country, even in soils with high aluminium levels. At Glenmore Station, where lucerne struggled to perform, lupin was the highest yielding sown legume.

Caucasian clover is continuing to show potential as a legume for use in high country environments. Additional results from the Lake Heron Station establishment experiment are required to confirm the initial indications that the second attempt at establishment was more successful than the first attempt.

Results from Glenmore Station and Bog Roy Station indicate that balansa clover struggles to re-generate in these high country environments, while lotus showed more potential. White clover production at Glenmore Station was similar to Caucasian clover and lucerne. Surprisingly, oversown lupin has been successful at Bog Roy.

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Site 1 – Glenmore Station

Overall objective

Investigate the effect of coulter type, lime rate and pre-sowing treatment (burn/herbicide) on the establishment and production of three legumes in a hill country environment. Updated in 2012 to investigate the effects of lime on the establishment of six legumes using a full herbicide and burn pre-treatment and to evaluate the effect of sowing rate of two lupin varieties at Nil and 3 t/ha lime.

Glenmore Climate

Three current rainfall values are shown in Figure 1.1 along with the long term mean for 1981-2010. Rainfall recorded on site (Glenmore Rain) corresponds closely with Tekapo Rain and with the Virtual Climate rainfall (Rain G18) which itself is a NIWA rainfall estimate for a point 2 km from the Glenmore site and based on the NIWA climate records. For the current 2013-14 season winter rainfall was more than adequate and followed by more than average rainfall in October. Spring pasture growth responded well. The summer period was the driest of the three summers that the experiments have been running at Glenmore leading to poor summer and early autumn (March) growth.

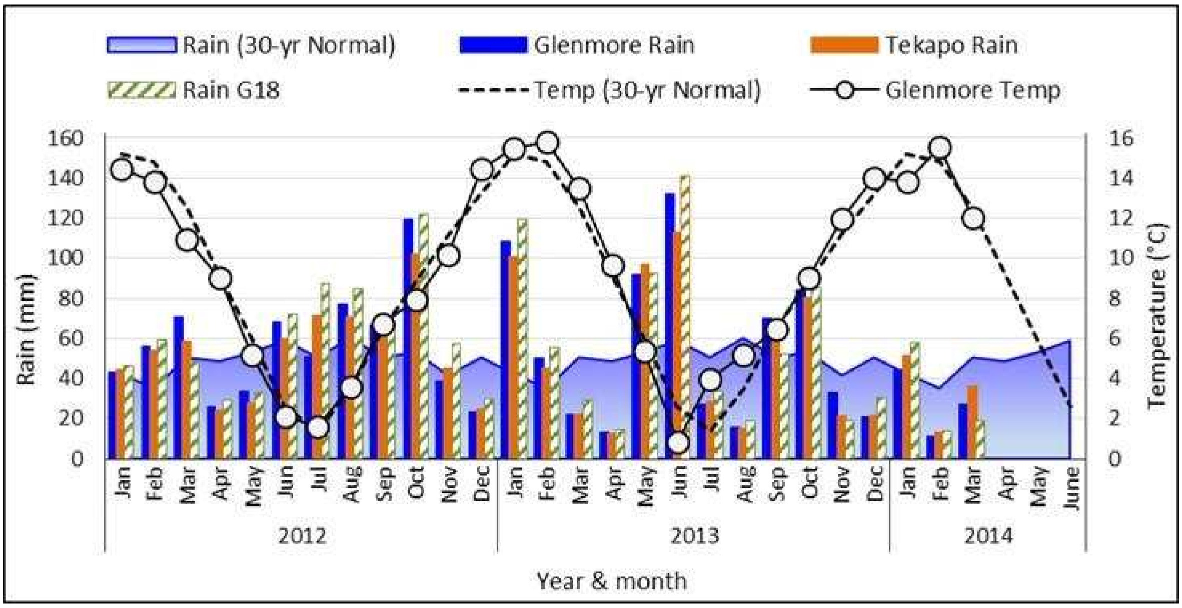


Figure 2.1 Monthly mean temperatures and monthly rainfall recorded on site (Glenmore Temp. and Glenmore Rain). Also shown are Tekapo Rain (NIWA Tekapo AWS climate station), rain from the NIWA Virtual Climate Station nearest to the Glenmore site (Rain G18) and the 30-yr temperature and rain means for Tekapo from NIWA CliFlo Database for Tekapo.

Exp.'s 3 & 4 – legume x drill type with herbicide and lime pre-treatments

<u>Experimental design and treatments</u>

Refer to the NZ Merino June Report 2013 for details of establishment and annual growth for 2012-13.

<u>Results</u>

Lupin seedlings

There was no detailed data collected from this experiment other than a seedling count on 1 October 2013 in the lupin plots that had been sown in 2011 with the Taege drill and had produced seed during summer 2013. The mean seedling population from nine 0.1 m^2 quadrats was 538 plants/m^2 and ranged from 60 to 1700 plant/m^2. A few seedlings had 3 or more leaves which indicated autumn germination but most were at the cotyledon to 2-leaf stage only, indicating late-winter to spring emergence (Plate 1.1).

Plate 1.1 Regenerating lupin seedlings on 1 October 2013. Seed was produced the previous summer by plants sown in November 2011.

Persistence and growth of sown legumes

Photos were taken of plots on 1 October 2013, 2 December 2013, 31 January 2014 and 24 March 2014 (Plate 1.2). Resident grasses of Kentucky bluegrass, browntop and sweet vernal tended to dominate throughout. Volunteer white clover was present to varying amounts but inconsistent across the experiments. Plots were grazed in common across all experiments on 6-9 December with 1200 merino two-tooths. Regrowth after grazing was not rapid and clearly showed water stress after 7 weeks. Observations in March revealed no improvement.

Lucerne continued to persist with little loss in population from the previous year, but the growth was lacking in vigour and few plants were a healthy green. After grazing in December the lucerne regrowth appeared drought-stressed, whereas the resident grasses, the sown Caucasian clover and the lupin showed few outward stress symptoms. This was a strong indication that the lucerne lacked N-fixing rhizobia and/or root penetration through the acidic and toxic aluminium soil layer.

Individual lupin plants dominated the resident grasses, but with an overall population of fewer than five mature plants/m^2, their ground cover was <10% overall when viewed in December but up to 25% cover in the Taege drilled plots.

Caucasian clover was persistant and formed up to 50% of the ground cover where it had been sown.

Plate 1.2 Lupin plots from Experiment 3 (2.5 t/ha lime, foreground) and Experiment 4 (5.0 t/ha lime, background) sown on 15 November 2011. Photos were taken on 1 October 2013 (top left), 2 December 2013 (top right), 31 January 2014 (bottom left) and 24 March 2014 (bottom right).

Exp. 5 – Legumes x lime rates

Experiment 5 was sown in December 2012 into the space previously occupied by Experiment 2, sown in November 2011 (discontinued). Data for the establishment phase from December 2012 to 17 April 2013 were presented in the NZM June Report 2013.

Experimental design

The experiment was a strip-plot design with three replicates. Main plots were five lime rates (Nil, 0.5, 1.0, 2.0 and 5.0 t/ha) and sub-plots were six legumes. Three legumes (white clover, balansa clover and lotus) were included for their tolerance to water logging conditions to help assess whether water-logging may have been a factor in some of the poor establishment of the other legumes (lucerne, lupin, Caucasian clover) when sown in Experiments 1-4 in November 2011. Observations this year concentrated on the productivity and legume persistence in response to the five lime rates applied in May 2012.

Measurements

The whole paddock, including this experiment, was grazed for 2 days in mid-June 2013 by 800 merino ewes. Assessment the following spring and summer consisted of photographs of plots, capacitance probe measurements and visual assessment of sown legume yield fraction (20 October only) and quadrat cuts and botanical separations on 3 December 2013 and 25 March 2014 (Table 1.1). Lucerne plots were also harvested for DM yield on 20 October 2013 and on 31 January 2014 followed by mowing to 5-10 cm to promote a 6-7 week regrowth cycle for the lucerne. The whole paddock (2 ha) was grazed by 1200 merino two-tooths on 6-9 December for three and half days and 200 ewes for 7 days at end of March.

Table 1.1 Timeline of measurements and yield harvests for Experiment 5.

	2013				2014			
Activity	17 Sep	20 Oct	3 Dec	6 Dec	15 Jan	31 Jan	25 Mar	28 Mar
Photograph plots	✓		✓	✓	✓	✓	✓	
DM yield & legume fraction		pasture probe	✓			lucerne only	✓	
Mowing (hay cut)		lucerne				lucerne		
Grazing				✓				✓

Results

October

On 20 October, growth was well underway except for balansa clover and lotus, although small plants were present (Figure 1.2). Seed of the annual balansa clover had been hand spread the previous autumn, but seedlings were sparse. The strong growth of balansa the previous summer suppressed weed growth and left a large amount of dead stem litter.

Volunteer white clover was common, and its presence within the sown white clover plots was estimated from its %cover in the Caucasian clover plots. Lupin dominated the early spring growth producing up to 4.5 t DM/ha. (Figure 1.3). The only species to show a significant lime response was lucerne. Lupin supressed most other species. Grasses were mainly browntop, Kentucky bluegrass and sweet vernal.

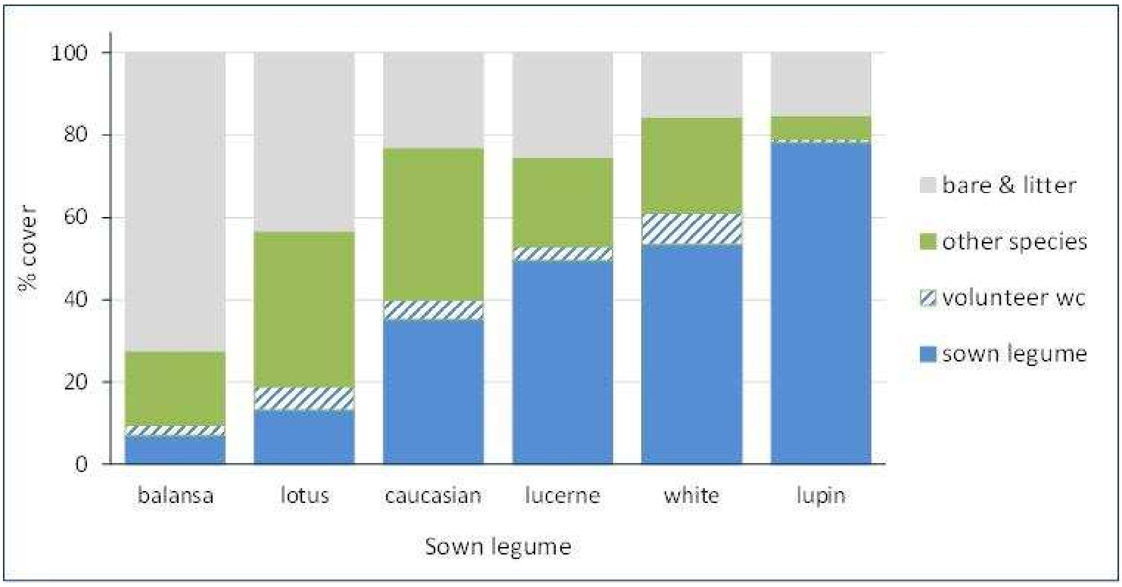


Figure 1.2 Percentage cover of the sown legume, other species and bareground & litter on 20 October 2013.

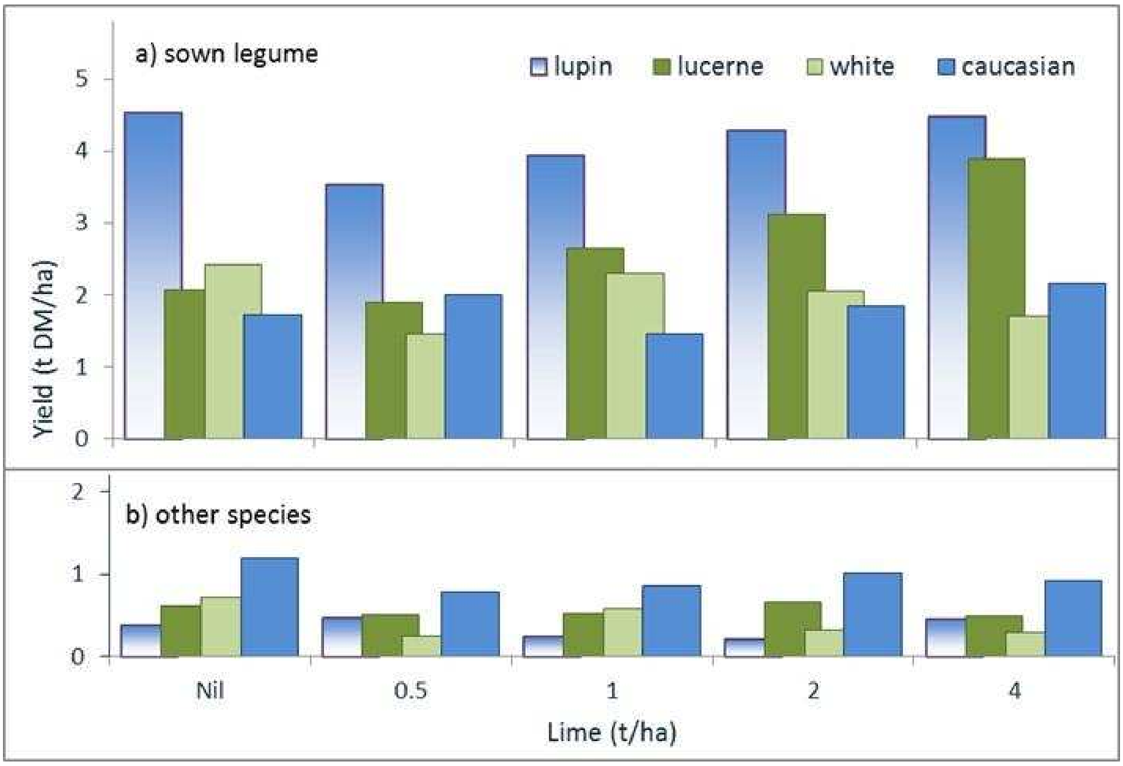


Figure 1.3 Dry matter (DM) yield of a) the sown legumes, and b) the contribution from other species in response to five lime rates, on 20 October 2013. Plots were sown on 12 December 2012.

December

Total spring DM yield (Figure 1.4) was over 8 t DM/ha for the Caucasian and lupin plots. Lupin was the dominant sown legume at 7.5 t DM/ha. The sown legumes (white clover, lucerne and Caucasian clover) produced 3.56, 3.53 and 4.42 t DM/ha, respectively. **N.B.:** the yield of lucerne at 20 October was added to the December harvest because it had been cut to 5-10 cm afterwards. Caucasian clover plots had a significant content of volunteer white clover. There was likely a similar proportion of volunteer white clover in the white clover plots that was not separated out. Other legumes were the adventive annual clovers namely striated, suckling and haresfoot clover. The resident grasses (Kentucky bluegrass, browntop and sweet vernal) dominated the balansa clover and were prevalent throughout except where heavily suppressed by the lupin.

There was no statistically significant effect of lime on the DM yields, but lucerne had shown a lime response similar to the October result above.

All plots were grazed in common after assessment. Measurements of residual were taken from lupin and Caucasian clover plots. Utilisation was about 65% for the Caucasian clover and 35% for the lupin. However sampling was inadequate for a statistical analysis.

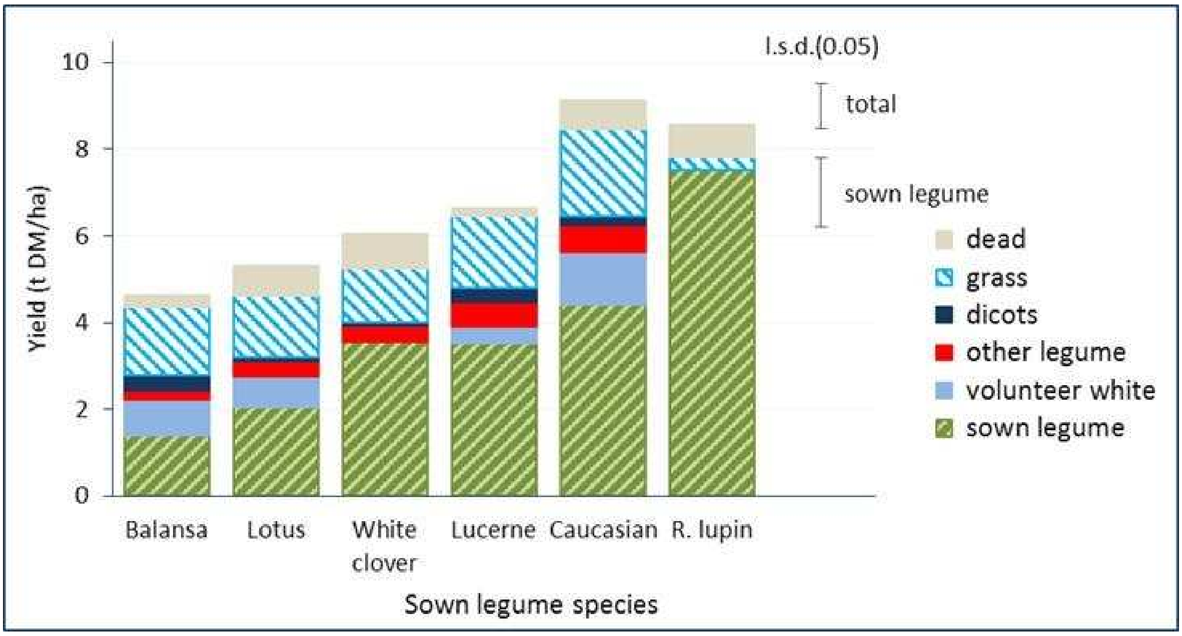


Figure 1.4 Yield of sown legumes and other species on 2 December 2013. Least significant differences (l.s.d.; P<0.001) are shown for the effect of species of sown legume on yield.

March

Lupin growth started slowly after the grazing in December but grew well during late February and March, while most other species, including volunteer grasses, showed drought stress (Figure 1.5). Lucerne grew well to the middle of January, producing about 90% of its summer DM yield, but then developed severe moisture stress symptoms by 31 January without flowering. The dicot weeds in lupin plots was almost entirely fathen

(*Chenopodium album*) which re-established in the bare patches between the lupin plants. Grasses were Kentucky bluegrass, browntop and sweet vernal.

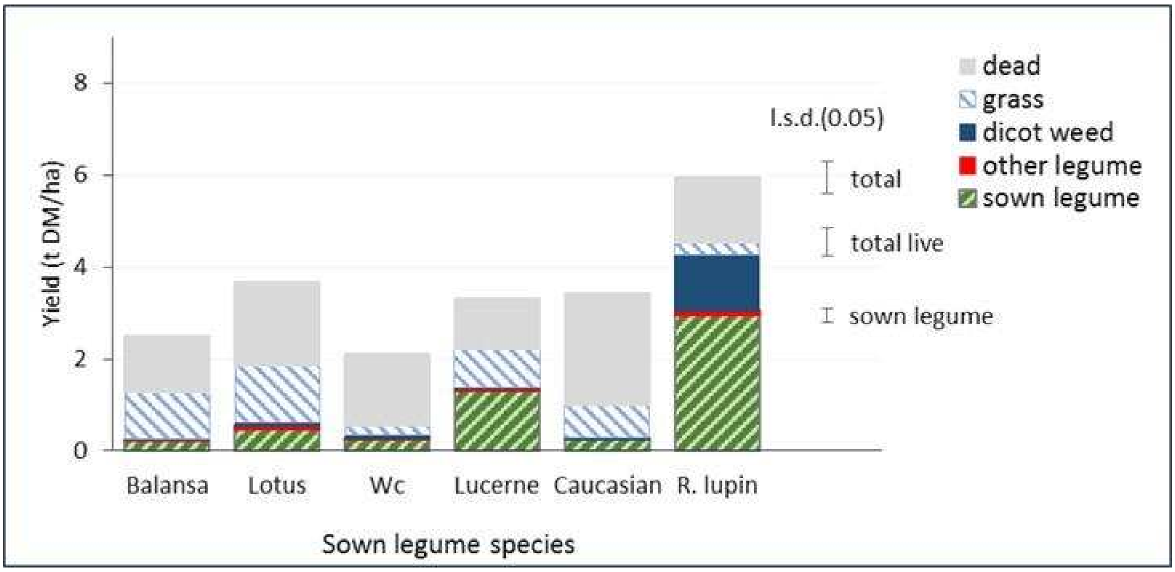


Figure 1.5 Yield of sown legumes and other species on 25 March 2014. Least significant differences (l.s.d.; P<0.001) are shown for the effect of species of sown legume on yield.

Total sown legume yield

'Russell' lupin was the highest yielding sown legume for the period of September 2013 to 25 March 2014 (Figure 1.6). The re-invading resident grasses produced most of the other live DM. White clover and Caucasian clover also produced a relatively large amount of dead material in late summer and autumn (Figure 1.6). The long growth periods between the December and March harvests/grazings for all but lucerne (mid-October and late-January harvests as well) resulted in leaf senescence of the legumes and reproductive growth in the lupins and resident grasses.

Sown legume	Legume yield	Other
R. lupin	10.44	1.89
Lucerne	4.83	3.85
Caucasian	4.65	4.82
White	3.80	2.00
Lotus	2.51	3.95
Balansa	1.51	4.01
l.s.d. (0.05)	1.66	

Figure 1.6 Total annual legume yield (t DM/ha) and other live (mostly grass) yield for the 2013-14 season at Glenmore for six species of sown legume.

Exp. 6 – Lupin sowing rates (sowing rate x lupin variety x lime rate)

Experiment 6 was sown in December 2012 to examine the responses to sowing rates of 2, 4, 8, 12, 16 and 32 kg/ha for 'Russell' and 'Blue' lupin with and without lime. A manuscript has been prepared covering the experiment to end of March 2014 and submitted to NZ Grasslands Association for the November 2014 conference in Alexandra. It is reprinted here in full as Appendix 2.1.

Plate 1.3 Early spring growth of lupin (and cocksfoot) in Experiment 6 at Glenmore, 1 October 2013. In the centre plot 'Russell' lupin is on the left and 'blue' lupin on the right, both sown at 12 kg/ha in December 2012.

Exp. 7 – Lucerne and lupin demonstration area

Experiment 7 was sown on the same date as Experiments 5 and 6 (December 2012). Lupin and lucerne were sown around the edges of Experiments 1, 3, 4, 5 and 6. These areas had been sprayed with glyphosate, followed by grazing, burning and 3t/ha of lime applied in autumn 2012. Experiment 7a was sown in 10 kg/ha lucerne and 2 kg/ha cocksfoot (Plate 1.4, top); Experiment 7b was sown in 12 kg/ha 'Russell' lupin along the fence beside the Godley Peaks road; and Experiment 7c on an area of moderately deep vs very shallow (stony) soil on the far right of the experimental area (Plate 1.4, lower) was sown with 4 kg/ha 'Russell' lupin and 2 kg/ha cocksfoot in the centre, and lucerne and cocksfoot around the perimeter.

Plate 1.4 Glenmore experimental paddock (top) showing a strip of lupins growing nearest the Godley Peaks Rd (Experiment 7b), an area of lucerne and cocksfoot out-lined in yellow (Experiment 7a) beside the lupin strip and a second block of lupins on the right (Experiment 6). The lower photo shows the block of lupins and cocksfoot at the lower end of the paddock (Experiment 7c).

Dry matter yields from these areas (Figure 1.7) showed similar yields to the other experiments. The high strike of cocksfoot, where sown, produced a high yield of cocksfoot in the 2013-2014 season. Lupin did poorly on the very dry stony soil and exceedingly well on the moister hill slope. Lupin plants, though absent from the DM yield from the dry site in March, were present but very small. Lucerne started well in spring but again failed to outperform other species during the summer dry period.

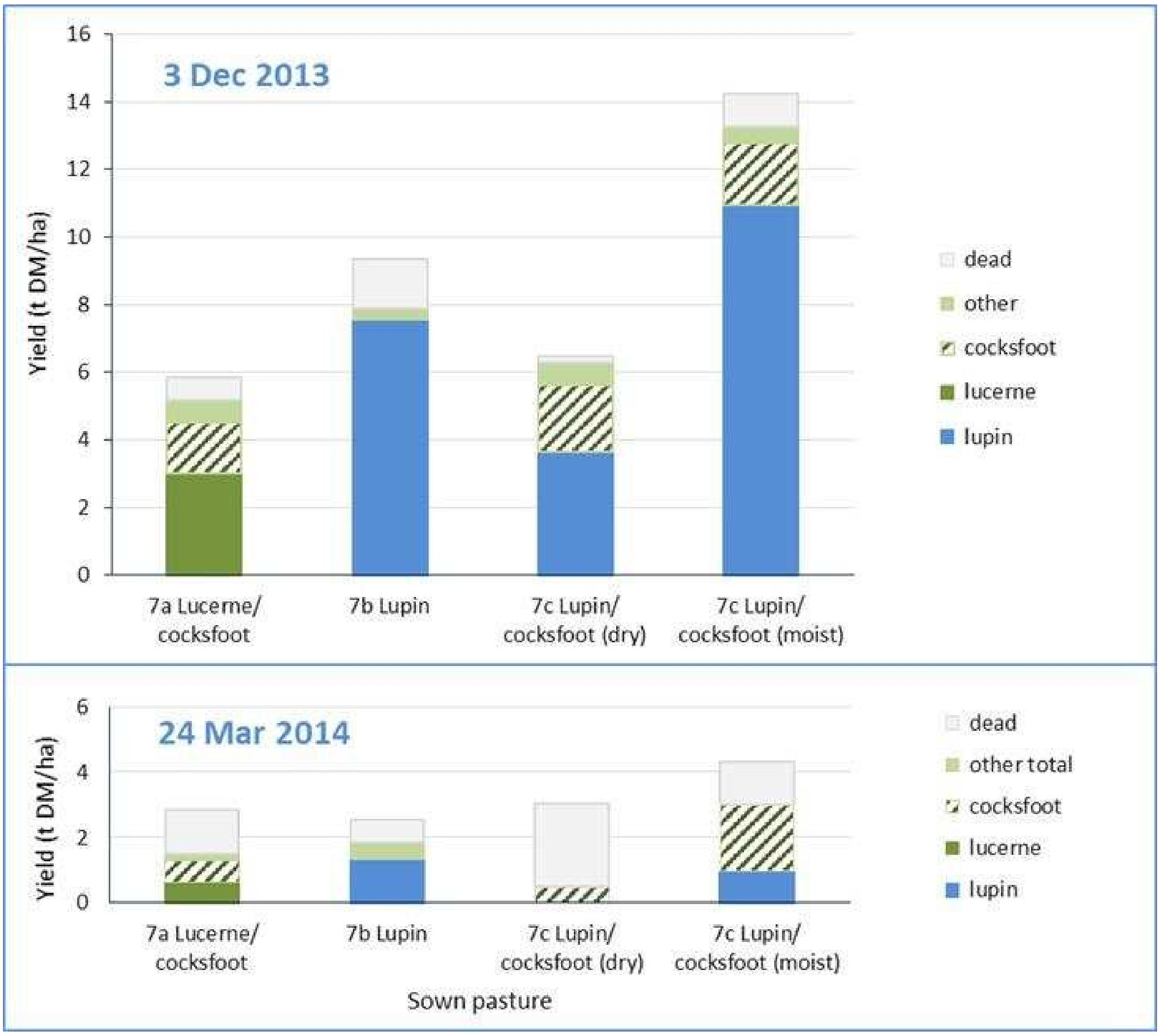


Figure 1.7 Yield of pastures at Glenmore Station, sown in December 2013, during their first full growth season on areas not included in the main experiments (Exp.'s 3, 4, 5 and 6).

<u>Autumn grazing and winter survival of lupins</u>

All plots were grazed in mid-June 2013. Snow partially covered the plants and sheep were only able to do a light grazing. Then a half meter of snow or more covered the site for 3 weeks until early July (Plate 1.5). Frosts were severe at the end of June with the air temperature descending to -10.5 °C on 29 June but the blanket of snow protected the plants as inferred by the non-freezing soil (Figure 1.8).

Observations in mid-September and plant counts on 1 October 2013 showed that all marked plants were still present and largely unhindered. While some drought stressed plants were quite small at the end of autumn they appeared unaffected by the grazing and winter frosts (Plate 1.6). Cocksfoot plants had slightly shorter leaves where they had been grazed.

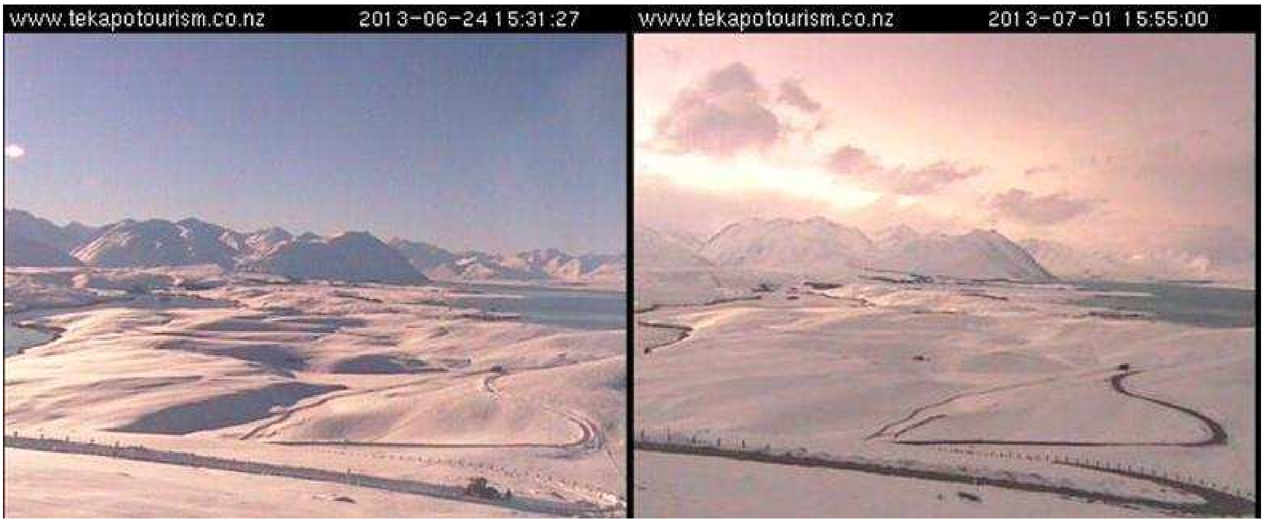


Plate 1.5 Snow cover in late June 2013 at Glenmore Station (middle distance) viewed from Mt. John, Lake Tekapo. Photos by http://www.tekapotourism.co.nz/webcam.html.

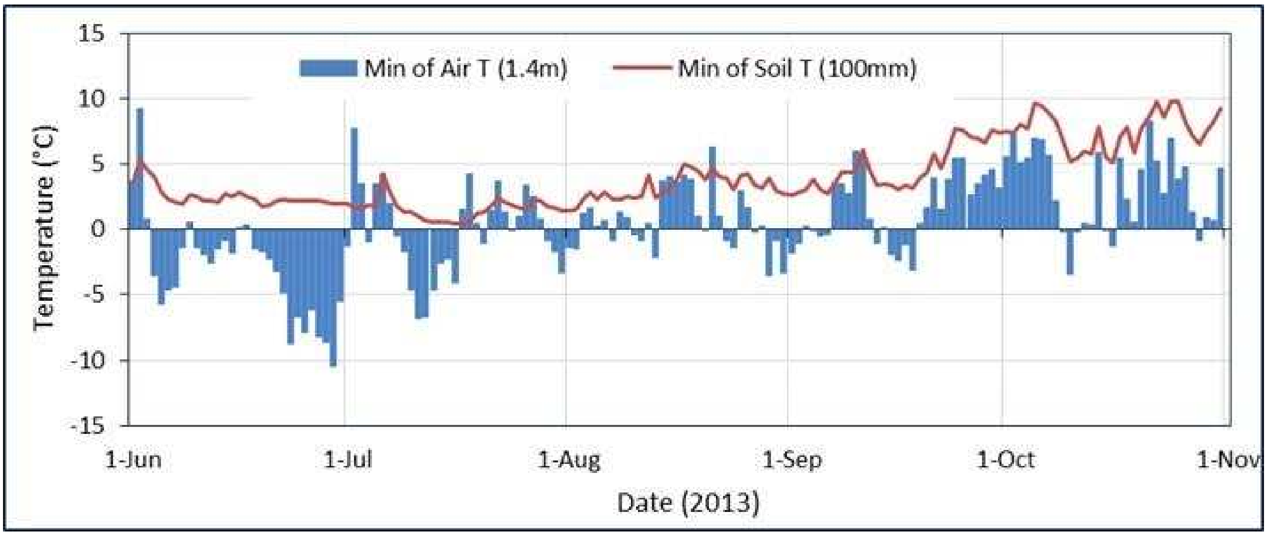


Figure 1.8 Daily minimum air and soil temperatures at Glenmore during June-October 2013.

Plate 1.6 Lupin/cocksfoot on 19 September 2013 at Glenmore Station showing the effect of autumn grazing to the left and no grazing to the right of the fence (above) and a small marked lupin plant showing early spring growth (right).

Site 2 – Bog Roy Station

Exp. 1 – Lucerne comparative experiment

Primary objective

Quantify the seasonal production of lucerne and ryegrass pastures at varying altitudes in response to temperature, soil type and aspect, compared with unimproved pastures.

Experimental design

Exclusion cages were placed in eight different paddocks across the property. Each cage measured 0.6 x 0.6 m (0.36 m^2) and enclosed a representative sample/area of the paddock. Sown species in these paddocks included lucerne and lucerne/grass mixes, and were compared with unimproved pastures and irrigated ryegrass/white clover pastures. Measurements were discontinued for the Baleage paddock because it was sown to ryecorn in 2012. Pasture heights were recorded to build a relationship between height and dry matter yield. A number of quadrats were also harvested from whole paddocks prior to and after grazing by various mobs of sheep during November 2013 to February 2014.

Further details regarding this experiment can be found in Appendix 2.2.

Results

Dry matter (DM) production was greater for the lucerne paddocks (Figure 2.1). The DM yield from the unimproved Bog Roy Hill up to November was largely due to the high content of annual striated clover (*Trifolium striatum*), Kentucky bluegrass and downy brome.

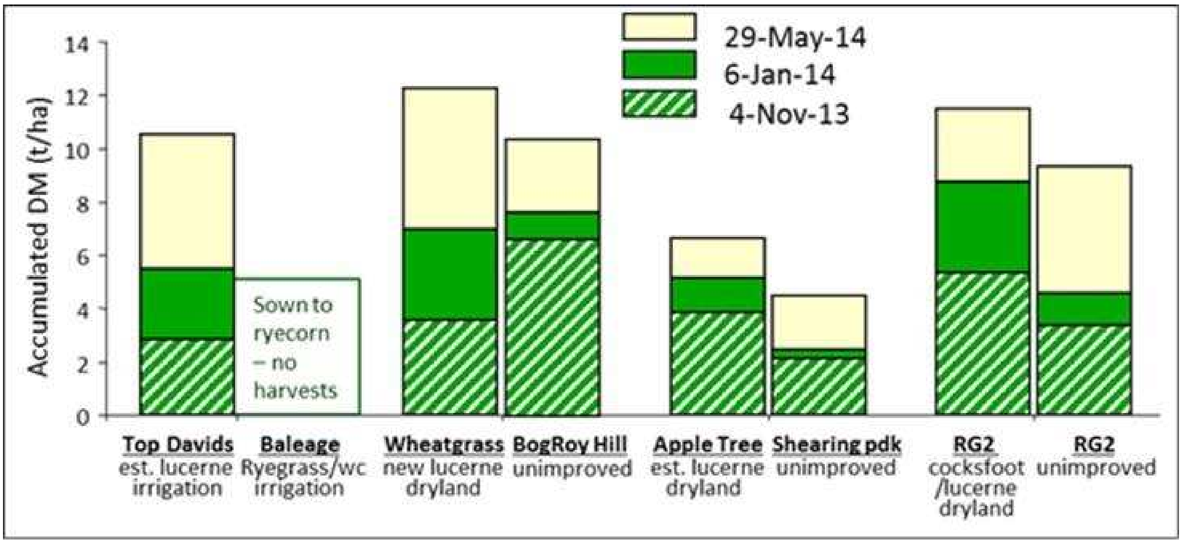


Figure 2.1 Accumulated DM yield from cage cuts at Bog Roy Station, September 2013 – May 2014. Data presented are in paddock pairs (lucerne sown paddock, then the 'grass' or unimproved paddock).

DM yield estimates from the cage cuts showed growth continuing into January in response to rainfall in spring and early summer (Figure 2.2), followed by very dry conditions in February and March. Also shown are the rainfall data available from the NIWA (National Institute of Water and Atmospheric Research) virtual climate station located about 2.7 km WSW of the Bog Roy homestead. This year was the driest of the three years of monitoring (starting form spring 2011) and slightly less than the 40-year mean.

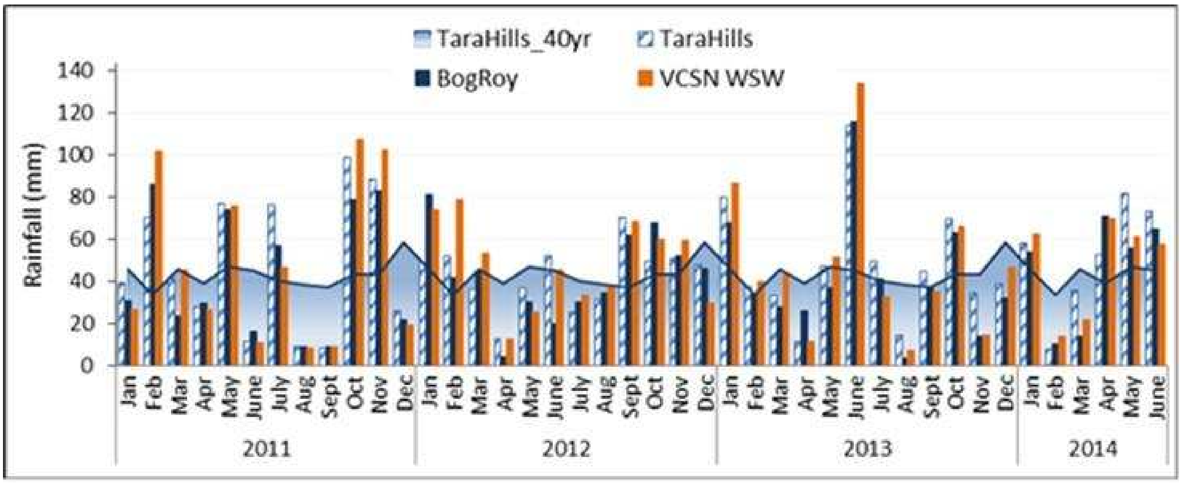


Figure 2.2 Monthly rainfall at Bog Roy Station Tara Hills and nearby NIWA virtual climate station (WSW). (Rainfall data courtesy of NIWA CliFlo online database).

The regression relationships between lucerne height and DM yield from harvested cage samples show about 60 kg DM/ha per cm of height during the spring and early summer declining to less than 40 kg DM/ha/cm during the late summer and autumn (Table 2.1 and Figure 2.3). However the variability is large, as seen by the low R^2 values for some months. The extreme outlier value in May shows the effect of a large amount of autumn grass growth (80% of the total DM), mostly rip gut brome and downy brome (*Bromus diandrus* and *B. tectorum*) in the Wheatgrass paddock (Plate 2.1).

Table 2.1 Regression coefficients for estimating lucerne DM yield (kg/ha) from height (cm) measurements of the cage cuts sampled at monthly intervals and of quadrat cuts from mob stocked paddocks before and after grazing.

	Lincoln data – long term		Bog-Roy (2012- 2014)
Month	**Pre-graze**	**Post-graze**	**Pre-graze (cage sample)**
Sep	105	60	96
Oct	100	55	67
Nov	80	51	64
Dec	65	48	58
Jan	60	46	61
Feb	60	45	57
Mar	60	45	37
Apr	60	45	32
May	60	42	

* January data was from a long rotation of 7 weeks

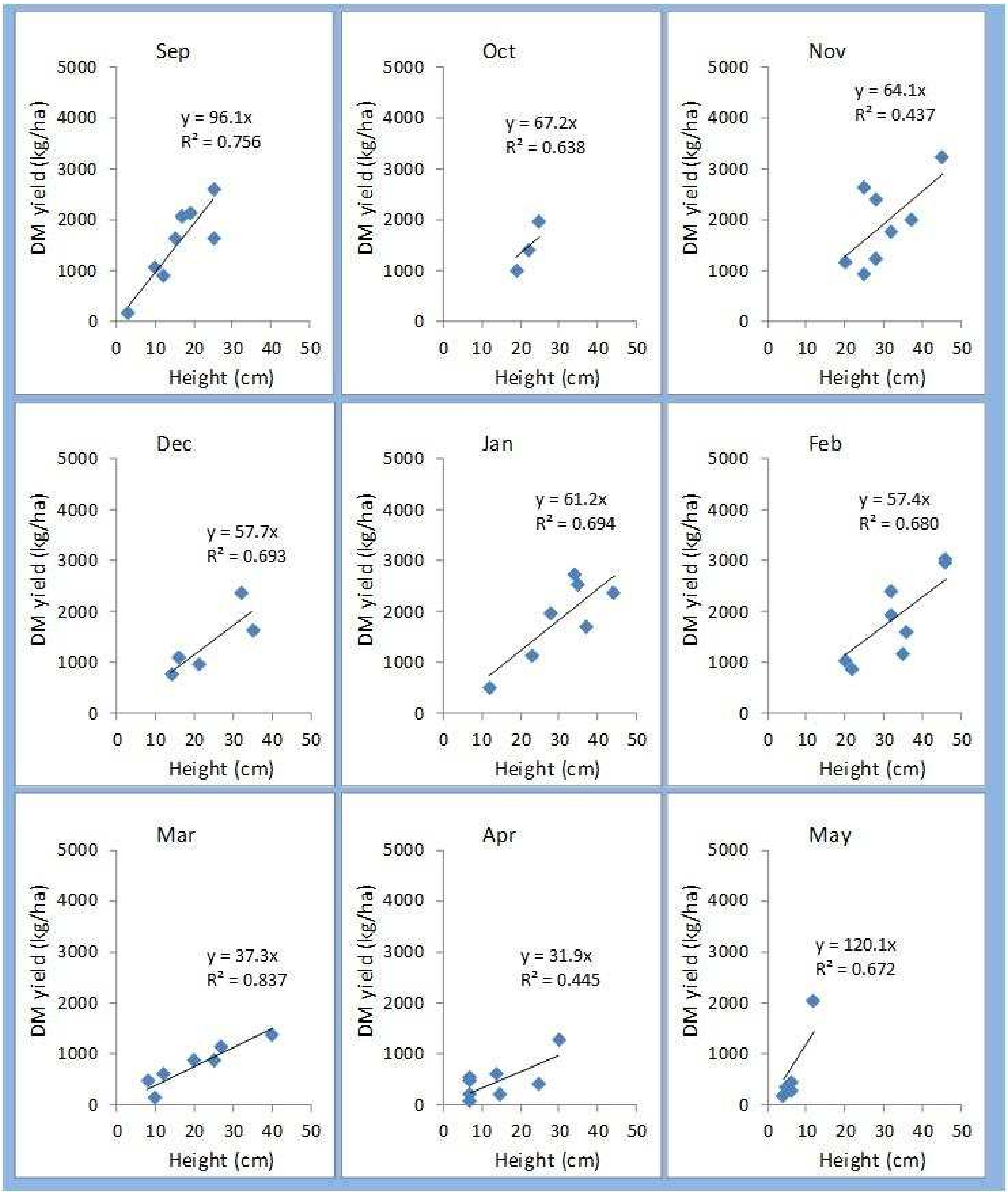


Figure 2.3 Regression relationship of DM yield vs. plant height from lucerne caged plots at Bog Roy Station, combined for the 2012-13 and 2013-14 seasons.

Plate 2.1 Wheatgrass paddock in December with abundant lucerne. The brome grasses (background) became more dominant in May when lucerne was shutting down with the lower temperatures.

The dataset from Bog Roy, derived from the regressions shown in Figure 2.3, is very small at this stage compared with the Lincoln dataset but shows that with more data a farm specific relationship between height and DM yield can be determined.

In Table 2.1 the samples taken from whole paddocks were often from more mature plants (5-7 weeks) compared with 4-5 weeks growth from the cage cuts. The paddock dry matter yield was estimated by measuring the canopy height and using the information given in Table 2.1.

<u>Whole paddock dry matter yield</u>
Figure 2.4 shows the regressions for the DM vs. height relationship for quadrat harvests from whole paddocks before and after grazing by various mobs of sheep. These regressions indicate a much higher pre-graze DM:height ratio than those from the cage cuts most likely due to the greater amount of stem thickening of the older plants from the paddock samples. The negative R^2 values for the post-graze DM:height regressions are probably indicative of the difficulty in measuring post grazing heights once the canopy is opened up.

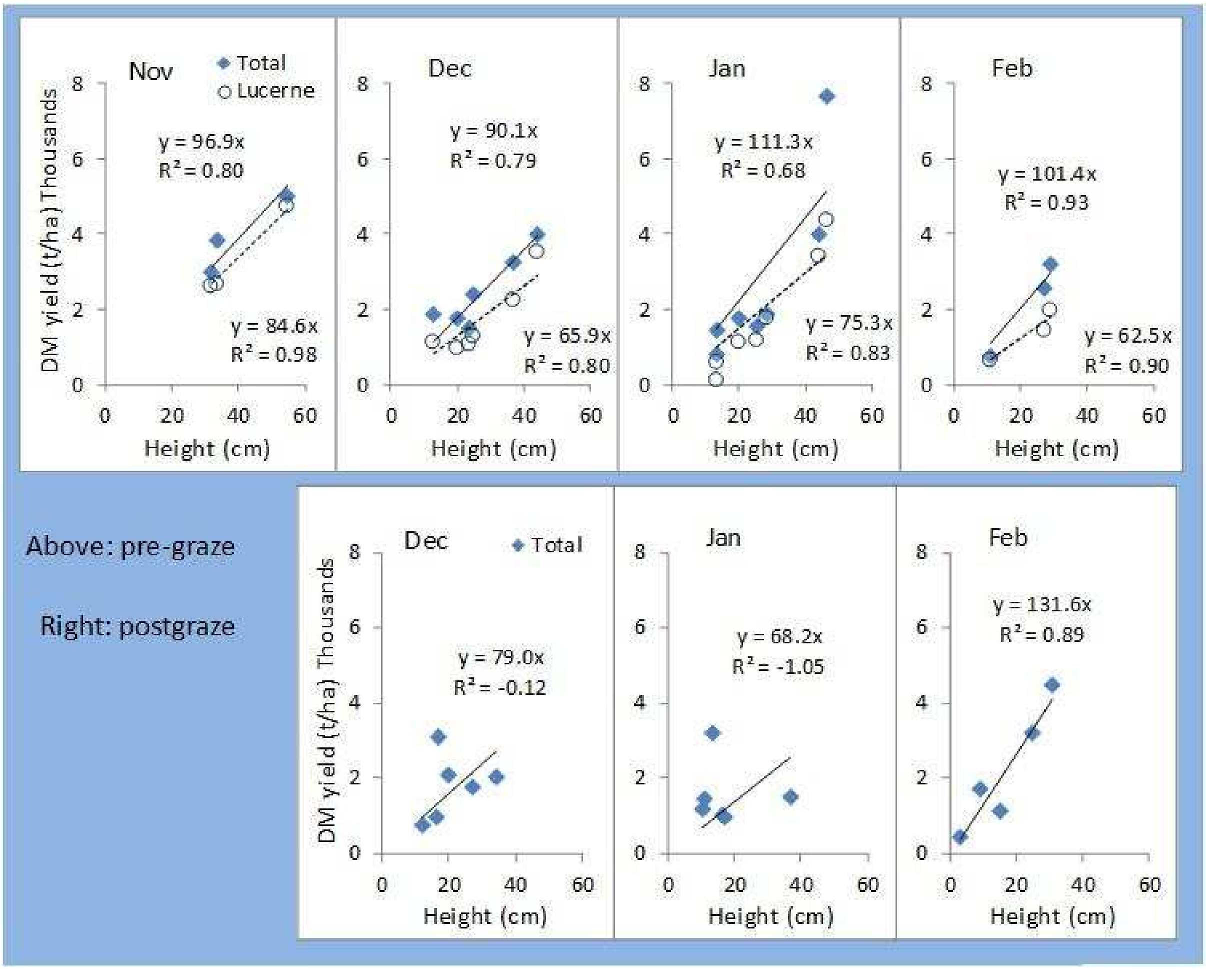


Figure 2.4 Regression relationship of total and lucerne DM yield vs. plant height from quadrat cuts at pre-grazing (Top) and total DM yield vs. plant height at post-grazing (Bottom) of lucerne paddocks at Bog Roy Station for the 2013-14 season. N.B. the regression coefficients are shown as kg DM/ha/cm of sward height.

For the whole paddock yields (Figure 2.3 and Table 2.2) the pre- and post-graze regression coefficients from the Lincoln data (Table 2.1) were used to estimate the DM yield at Bog Roy. Example charts of yield and grazing history over the growing season for five paddocks (out of 19) are shown in Figure 2.3 and the total paddock production shown in Table 2.2.

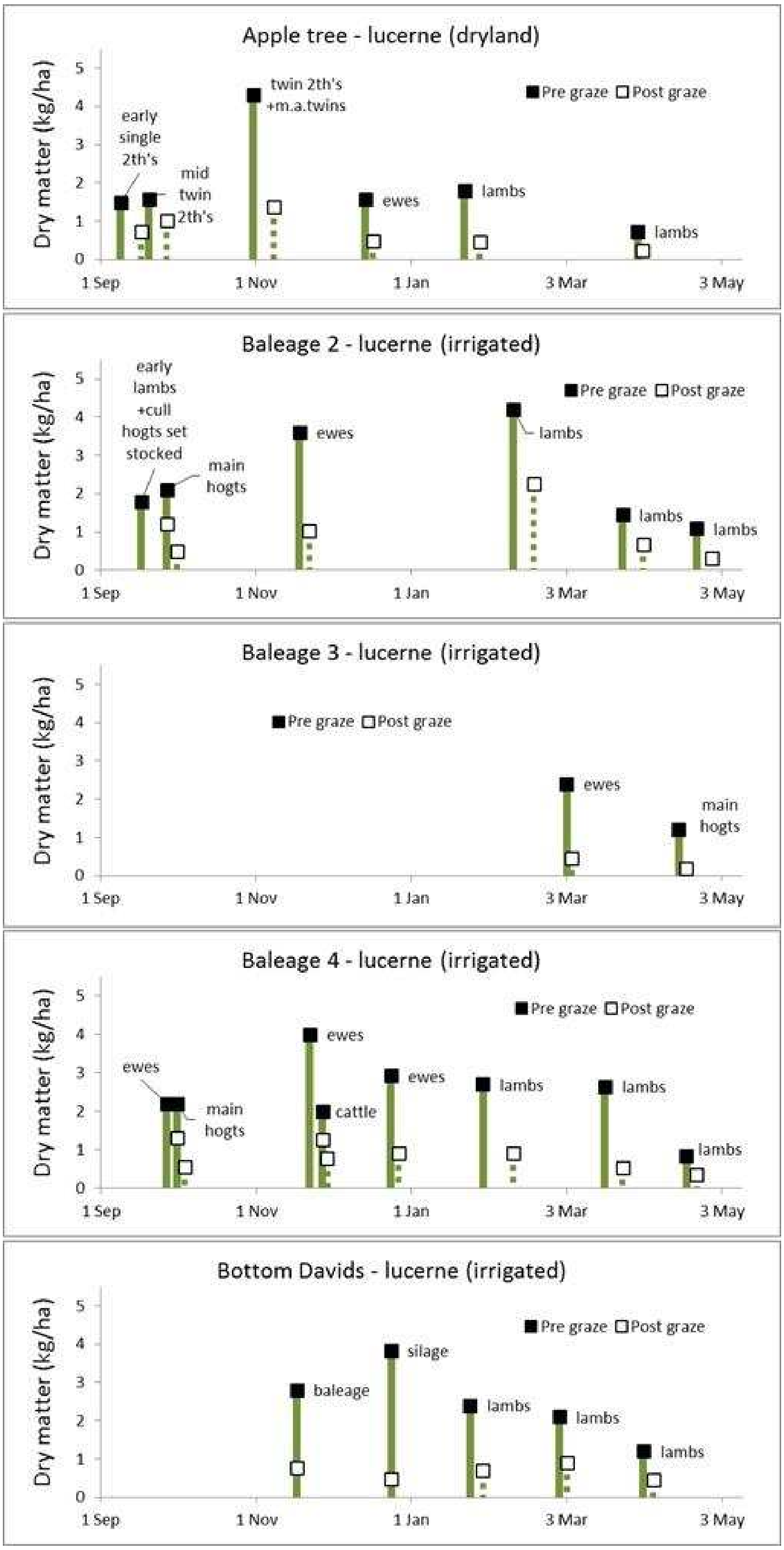


Figure 2.5 Paddock dry matter yield and mob grazing history at Bog Roy Station during the 2013-2014 season. Only 5 out of a total of 19 paddocks are shown here.

Table 2.2 Dry matter (DM) yield and utilization (Util.) under cutting and mob stocking for lucerne paddocks at Bog Roy Station for the 2013-2014 season. The number of silage or baleage cuts and grazings for each paddock are shown (No. of harvests) but exclude set stocked grazing of some paddocks early in spring. DM is estimated from pre-grazing and post-grazing heights as shown in Table 2.1.

		Cut for baleage or silage			Mob grazing			Total DM consumed
Pasture type & Paddock	Area (ha)	No. of harvests	DM (t/ha)	Util. (%)	No. of harvests	DM (t/ha)	Util. (%)	(tonnes per paddock)
lucerne (dryland)								
Apple tree	9.7				6	7.1	61	42.3
Bottom Shearing	20				4	5.8	66	75.9
Middle Shearing	16.2				2	1.9	39	11.7
Mutton	12				5	4.7	57	32.3
Roadside Shearing	12.9				3	4.5	50	28.8
Slope	7				6	8.8	58	35.7
Top Saddle	8				6	8.9	55	38.8
Wheatgrass	10				5	4.8	55	26.2
lucerne (irrigated)								
Baleage 2	8				5	7.7	64	39.2
Baleage 3	4				2	3.0	83	9.9
Baleage 4	7				8	12.9	65	58.2
Bottom David's	7	2	5.4	80	3	3.7	64	40.3
David's	7	2	4.5	60	4	4.5	62	38.8
lucerne & cocksfoot (dryland)								
R G 1	9.2				6	7.1	60	39.1
R G 2	8.7				5	6.5	67	37.9
R G 3	11.4				6	8.1	66	60.9
Rough Gully Luc	9.8				6	6.3	66	40.8
Top Lake	8.5	1	3.0	93	6	6.3	61	48.3
lucerne & cocksfoot (irrigated)								
Btm Lake	8.5				6	9.3	62	49.0

Plate 2.2 Slope paddock in December at Bog Roy Station before and after grazing.

Exp. 2 – Annual clovers in fenced off exclosure

Initial sowing of annual clovers and lucerne was on 22 Feb 2012. There was little survival or regeneration the following year and half of each plot was re-sown on 6 May 2013.

On 21 October 2013 all plots were inspected for seedlings/plants of the sown species. Only a few balansa plants and one sub clover plant were present in the plots originally sown on 22 Feb, 2012. There were a few more plants from the 6 May, 2013 re-sowings. For these autumn sown plots, a 0.01m^2 quadrat was thrown down 10 times along the length of each plot and the presence/absence of each sown species noted. Presence in the plot, but not in the quadrats, was also noted. The summary of the presence/absence data is shown below as plant density (Table 2.3). Balansa clover showed the most promise but with the small sample size the results were numerically quite variable. Individual balansa clover plants had fewer than six leaves (Plate 2.3).

Table 2.3 Annual clover and lucerne populations at 21 October 2013 in the fenced-off enclosure at Bog Roy Station from seed sown the previous autumn.

Species sown	Plants per m^2	Standard deviation
'Bolta' balansa	28.3	21.4
'Force4' lucerne	3.3	5.2
'Prima' gland	1.7	4.1
'Rosabrook' sub	0.0	0.0
'Trikkala' sub	1.7	4.1
'Woogenellup' sub	1.7	4.1

The resident annual striated clover (*Trifolium stiatum*) dominated some plots at over 50% of ground cover but mostly formed 20-50 percent cover on the lower slope (Reps 4-6) and less than 20% on the upper slope (Reps 1-3). White clover was also common but not extensive. Kentucky bluegrass and hair grass (*vulpia* spp.) formed most of the grass cover on the lower slope and cocksfoot was common on the upper slope. Other grasses and broadleaf weeds were present.

Also on 21 October, annual legumes (and lucerne) were re-sown in a quarter of each plot where seed had not been re-applied in May, (Figure 2.6). Type C1 inoculum was used for all annuals. Lucerne seed was coated.

Further observations in January found only a few isolated plants of the sown species. Cocksfoot dominated on the steeper slope (Reps 1-3) and Cocksfoot, hair grass, Kentucky bluegrass, striated clover and volunteer white clover covered most of the rest of the site (Plate 2.4).

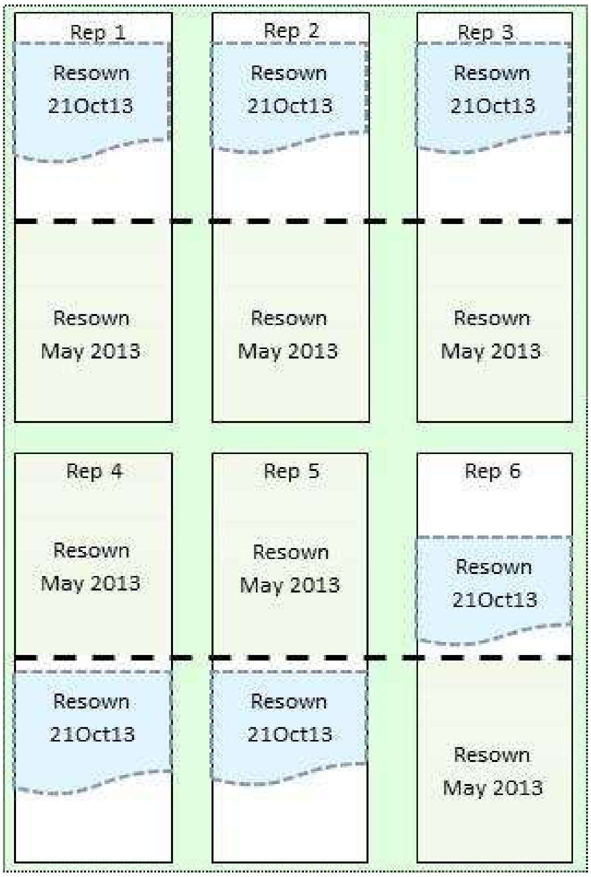


Figure 2.6 Position and re-sowing dates for annual clovers at Bog Roy Station within the annual legume enclosure after the initial sowing of plots in February 2012.

Plate 2.3 A lone balansa clover plant (with the leaf mark and serrated leaf margins) in a sea of striated clover on 21 October 2013 at Bog Roy Station.

Plate 2.4 Annual legume over-sowing enclosure at Bog Roy Station. Left: vigorous cocksfoot, but no legume on the steeper slope (October 2013). Right: grass continued to dominate the site into January 2014 as the pasture dried off.

Exp. 3 – Annual clovers on hill blocks

An annual clover mix was broadcast on three aspects at medium and high altitudes in autumn 2012 and spring 2012. Half of each plot was caged to protect seedlings from grazing.

Monitoring included:

- Visual assessment of survival through winter.
- Ability of annual clovers to flower and set seed.
- Ability of annual clovers to re-establish from seed.
- Dry matter production of annual clovers at different altitudes and aspects.
- Annual clover responses to fertiliser at establishment.

Survival, regeneration and yield

A selection of annual clovers (bladder, balansa, subterranean) and 'Russell' lupin seed were hand-sown on the hillside and covered with cages (0.7 m^2) on 26 September 2012. Monitoring during the spring and early summer of the following year (2013-2014) revealed little regeneration of sown species except for a few balansa clover and bladder clover plants and the survival of some lupins (Plate 2.5). The plots were harvested on 22 January 2014 and showed a predominance of the resident grasses, cocksfoot, volunteer white clover, haresfoot trefoil and lupin in some places (Figure 2.7). By this stage the bladder clover had seeded, died and did not feature in the DM yield. The resident suckling clover and haresfoot trefoil were still present but not as prevalent as in early December.

Overall the resident white clover and resident annual clovers provide a reasonable clover content. Lupin appears to be a useful perennial addition to the legume spectrum. Balansa clover and bladder clover show some promise but don't appear to be a commercial option at this stage. Adapting grazing frequency and spelling period to the benefit of resident clovers may be worth pursuing.

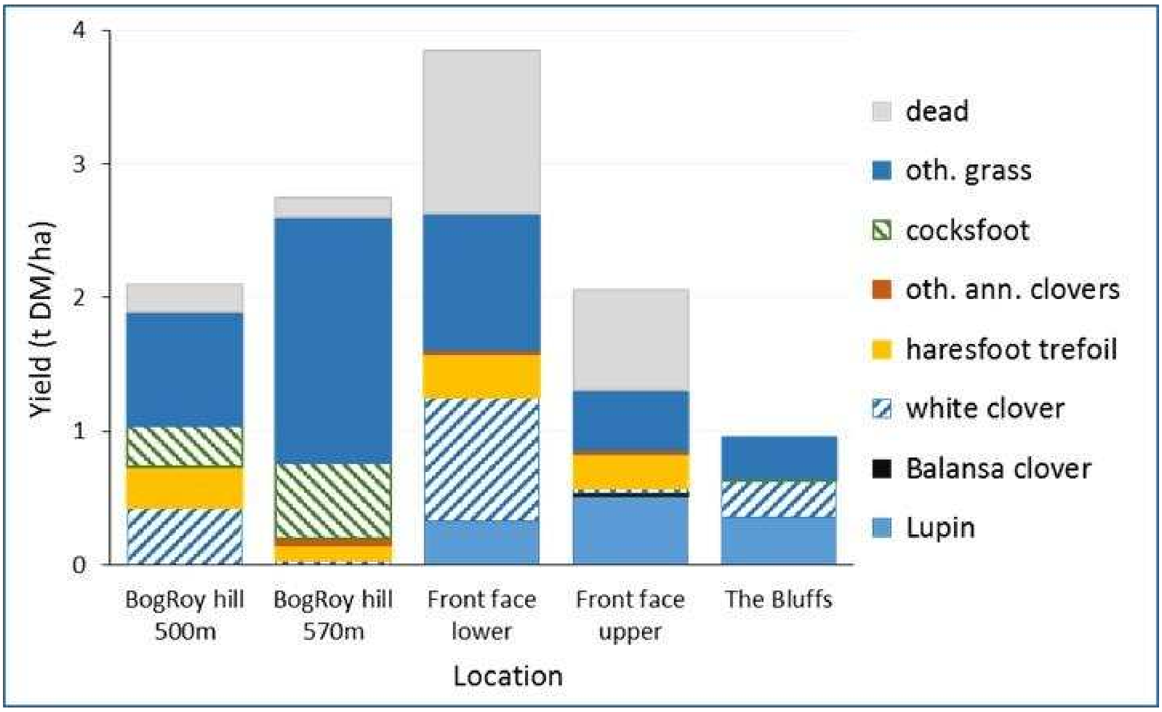


Figure 2.7 Dry matter yield from harvests on 22 January 2014 of annual clover caged plots on hill blocks at Bog Roy Station originally sown on 26 September 2012 and allowed to re-seed in their first year.

Plate 2.5 Annual legumes sown onto hill block paddocks at Bog Roy Station and protected from grazing using wire mesh cages. Photos taken on 5 Dec 2013.

Site 3 – Lake Heron Station

Exp. 1 – Established Caucasian clover in tussock grassland

Objective

Determine the rate of superphosphate required to maximise the dry matter production of a mature Caucasian clover pasture in the high country.

Experimental design

Combinations of four rates of superphosphate (0, 100, 200 and 400 kg/ha) and 0 or 5 t/ha of lime were applied to 12 x 20 m plots according to a 4 x 2 factorial randomised complete block design with four replicates (Plate 3.1). The two rates of lime were chosen to create two pH environments because it was suspected that the superphosphate response would depend on pH. The superphosphate was applied on 31 January 2012 and the lime on 28 February 2012.

Pasture production was measured on 28 November 2012 and 21 November 2013. From the harvested samples pasture yield and botanical composition were determined. Mineral analyses were also performed on leaf plus petiole samples collected on 9 May and 28 November 2012. Caucasian clover taproots and shoot growing points were assessed in March 2014 from 0.38 x 0.38 m quadrats dug to a depth of 0.1 m in each of the plots with the lowest and highest rates of fertiliser (Plate 3.3).

Plate 3.1 Mature stand of Caucasian clover on 29 January 2014. On the left is the experimental area which had been grazed last in early December 2013. The area on the right had not been grazed.

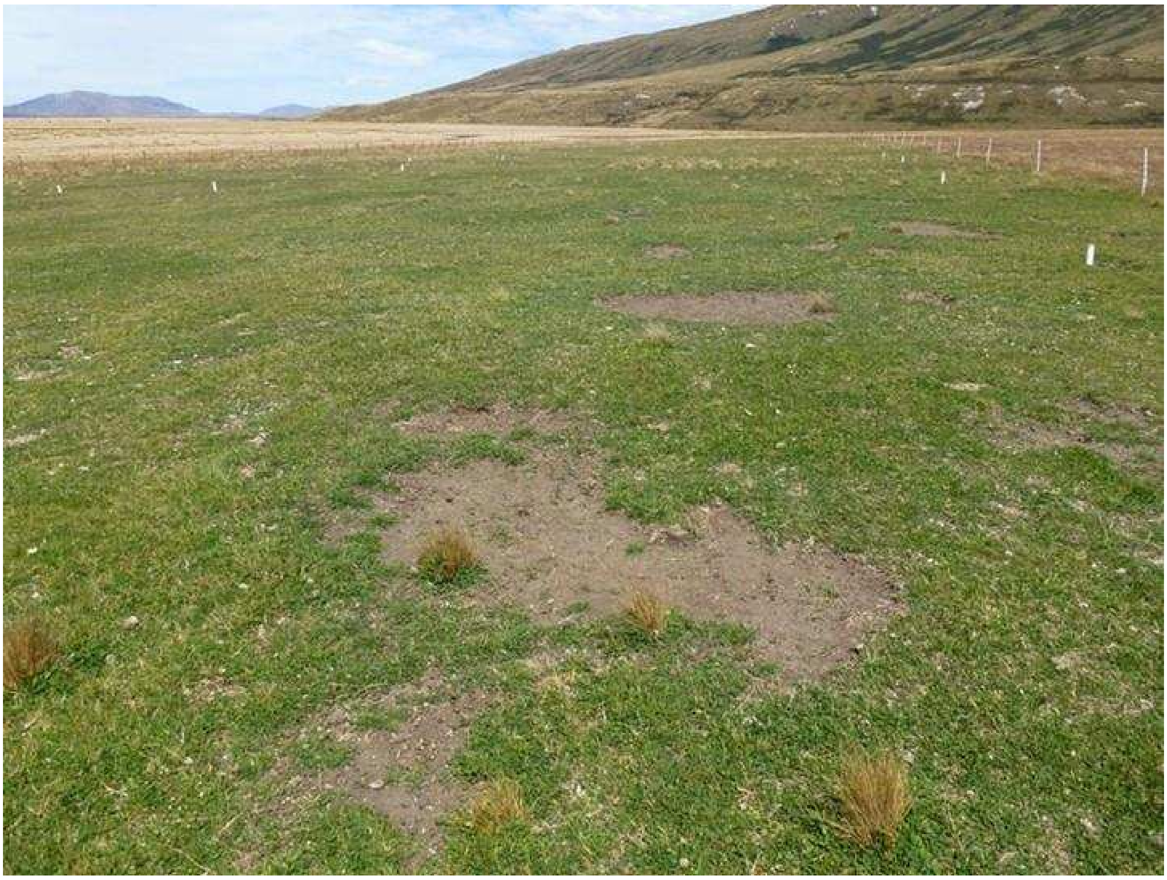


Plate 3.2 This photo taken on 29 January 2014 shows areas where sheep had scratched parts of the pasture to eat the sugar-rich rhizomes of the Caucasian clover plants.

Results

Pasture production

Pasture production in November (averaged over the two years) increased with superphosphate fertiliser application rate (from ~1.5 t DM/ha in the 0 kg/ha superphosphate plots to ~2.1 t DM/ha in the 400 kg/ha superphosphate plots), irrespective of the absence or presence of lime. The contribution of Caucasian clover to total pasture yield was not affected by superphosphate and lime, and averaged 67-77%.

Foliar mineral content

P, S and N contents in Caucasian clover foliar samples increased with increasing rates of superphosphate. The levels were, however, lower than those found in Caucasian clover growing in more fertile soils, even though soil Olsen P (11-14 mg/L) and sulphate S (8-10 mg/kg) levels were close to adequate in all treatments. The addition of 5 t/ha lime increased the pH from 5.5 to 6.0, and lowered Al from 2.4 to 0.6 mg/kg. The results suggest that a higher rate of superphosphate may be required to maximise Caucasian clover growth at this site.

Caucasian clover growing point population

In the presence of 400 kg/ha superphosphate and 5 t/ha lime, 1901 shoot growing points/m^2 were present, while only 1338 shoot growing points/m^2 were present when no superphosphate or lime was applied. The taproot population (9/m^2) and root and rhizome biomass (~5 t DM/ha) were unaffected by fertiliser and lime. The root and rhizome biomass (Plate 3.4) explains why Caucasian clover is able to survive in infertile soils and extreme environments. The lack of taproots, however, was unexpected and may have been the reason for signs of moisture stress in early summer.

Plate 3.3 An area of the mature Caucasian clover stand where a 0.38 x 0.38 m quadrat was dug to 0.10 m to measure root and rhizome biomass, on 19 March 2014.

Plate 3.4 Roots and rhizomes from a 0.38 x 0.38 x 0.10 m quadrat. The average root and rhizome biomass amounted to 5.1 t DM/ha and the population of taproots was 9/m^2.

Exp. 2 – Establishment of Caucasian clover and cocksfoot in tussock grassland

Background

Our first attempt to establish Caucasian clover into the native tussock pasture at Clent Hills failed. Plant analyses in autumn and spring after sowing indicated that the Caucasian clover plants were lightly nodulated and nitrogen deficient. This suggested that the inoculant that was used on the Caucasian clover seed was ineffective. Subsequent glasshouse work confirmed that 1) the soil at this site does not contain rhizobia that fix nitrogen with Caucasian clover and 2) fresh, commercial peat inoculant containing the rhizobia strain CC283b is effective on Caucasian clover. Therefore, it was decided to re-drill Caucasian clover into the same site and compare its establishment with lotus. We made sure that both species were freshly inoculated with effective inoculants before sowing.

Objective

T*o establish Caucasian clover and lotus into a native tussock pasture.*

Plate 3.5 Clent Hill "native" tussock pasture on 29 January 2014 after it was re-drilled with Caucasian clover, lotus, lucerne and cocksfoot on 22 November 2013.

Plate 3.6 Seedlings of a) Caucasian clover and cocksfoot, b) lotus and c) lucerne on 29 January 2014 after the native pasture was direct-drilled on 22 November 2013. Some Caucasian clover plants appear chlorotic such as the plant in the centre right in the top photo (a).

Methods

The trial site at Clent Hills (Plate 3.5), with 32 plots of superphosphate x lime treatments, was sprayed with Buster on 5 November 2013 and the tussock was mulched on 12 November 2013. On 22 November, 'KTA202' Caucasian clover seed was heavily inoculated with CC283b peat inoculant and 'Trojan' lotus seed was heavily inoculated with CC829 peat inoculant at Lincoln University and then taken to Lake Heron Station. The seed was direct drilled that afternoon, in strips across the existing plots. Both species were drilled at 8 kg/ha with 2 kg/ha of 'Vision' cocksfoot. 'Torlesse' lucerne (10 kg/ha) was also drilled across the plots, for interest-sake at the request of Philip (a nearby paddock was being drilled with 'Torlesse' on the same day). The whole paddock was mob grazed by wethers for 2-3 days after drilling.

Plant establishment was measured on 29 January 2014 (Plate 3.6), 11 weeks after sowing, from 16 plots (four replicates of 0 and 400 kg/ha super treatments, with or without lime).

Results

Plant population was low for all species but the established Caucasian clover plants were well nodulated and similar in size to lotus and lucerne, 11 weeks after sowing (Table 1). Some Caucasian clover plants were much smaller than others and appeared chlorotic (Plate 3.7). However, overall the Caucasian clover plants were larger and had more nodules (Plate 3.8) than the plants sampled 11 weeks after the first sowing (20 December 2011) at this site. These initial results are positive because they indicated that Caucasian clover may be able to establish by direct drilling into native grassland provided the seed is inoculated immediately before sowing and that the inoculant used is fresh and effective. There were no effects of superphosphate and lime treatments on plant establishment.

Table 3.1 Plant establishment on 29 January 2014 of Caucasian clover, lotus, lucerne and cocksfoot at the Clent Hills "native" tussock pasture.

	Caucasian	Lotus	Lucerne	Cocksfoot
Plants/2 m	6.8	6.3	11.2	7.6
Nodules/plant	5.8	3.6	2.8	-
Nodule score (1-5)†	2.49	2.21	2.01	-
Shoot dry weight (mg)	34.0	27.4	39.9	15.9
Root dry weight (mg)	21.4	8.5	16.6	5.9
Total dry weight (mg)	55.4	35.9	56.6	21.8

†1 = no nodules, 5 = abundant nodules

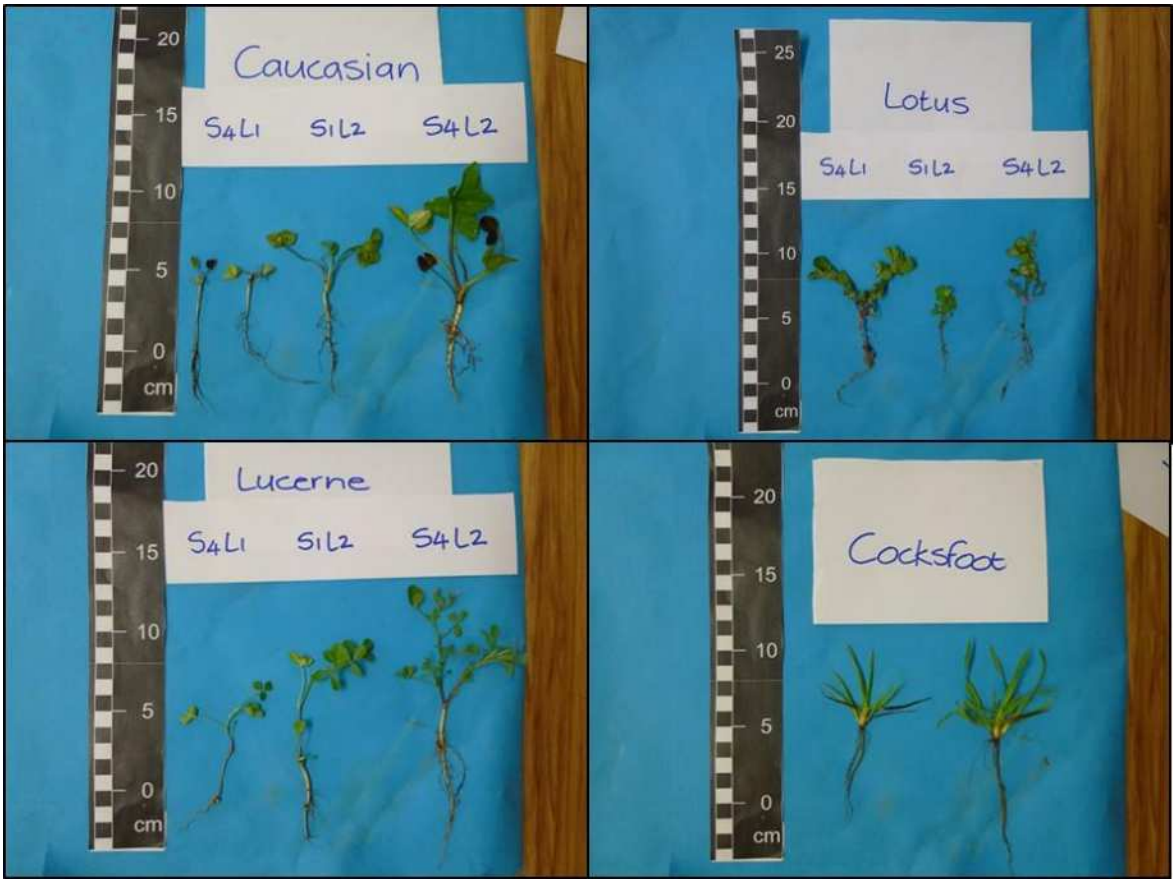


Plate 3.7 Seedlings harvested on 29 January 2014 at Clent Hills, Lake Heron Station, from plots that received 400 kg/ha superphosphate with no lime (S4L1), no superphosphate with 5 t/ha lime (S1L2) and 400 kg/ha superphosphate with 5 t/ha lime (S4L2).

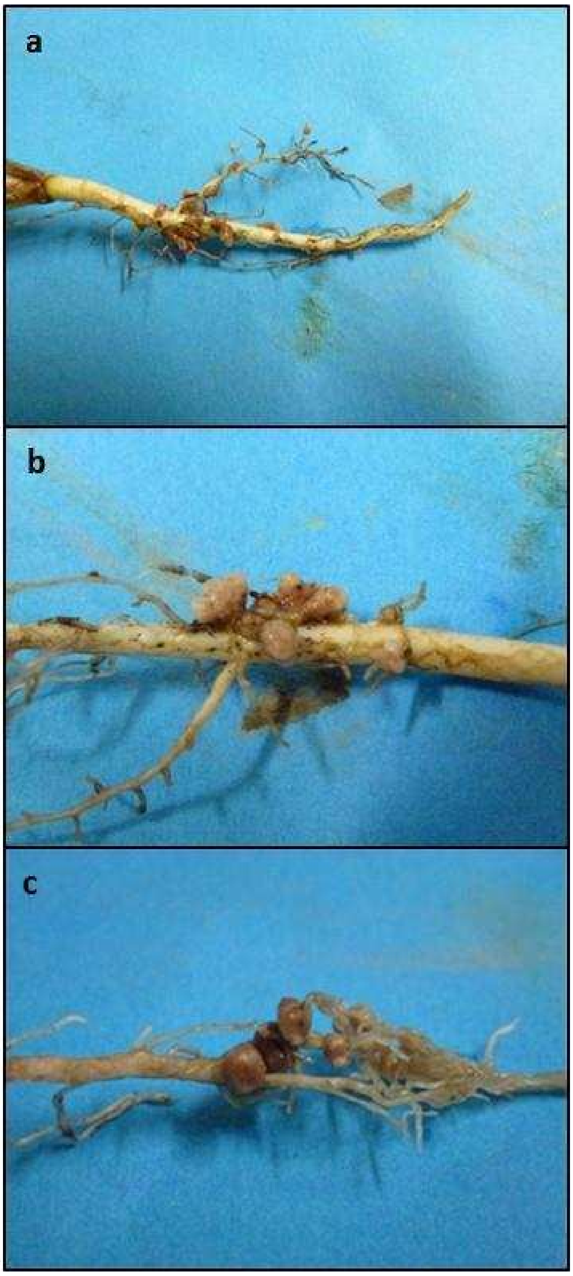


Plate 3.8 Nodulation on roots of a) Caucasian clover (score 5), b) lucerne (score 3) and c) lotus (score 3) plants harvested on 29 January 2014.

Exp. 3 – Glasshouse experiment

<u>Objective</u>

Examine some of the soil in the second experiment for inoculation and growth of Caucasian clover plants in the absence and presence of fertiliser and lime in the glasshouse.

<u>Experimental design</u>

Soil from the area next to Experiment 2 was collected to a depth of 0.2 m in March 2013 and used to set up a glasshouse experiment at Lincoln University. It was set up as a 2 x 3 x 2 factorial in a randomised block design with four replicates. The soil was mixed with appropriate rates of lime and fertiliser and placed into 1.3 L pots. Fertiliser and lime were applied as all possible combinations of the presence or absence of lime (3 t/ha), superphosphate (200 kg/ha), a nutrient solution (P, S, Mg, K, Ca and micronutrients at 70 mL/pot every 2-3 weeks after sowing) and inoculant. For the inoculated treatments, Caucasian clover seeds were inoculated before sowing.

<u>Results</u>

All inoculated plants were nodulated and had optimal foliar N levels regardless of fertiliser or lime, indicating that the inoculant used (CC283b) was effective (Plate 3.9). When lime was applied, the growth of inoculated plants was greater in fertilised plants than unfertilised plants (Figure 3 in the article/paper). The response in limed soil was due to a pH increase from 5.5 to 6.2.
Of the uninoculated plants, only 24 of the 36 plants were lightly nodulated, and all plants were 7-24% the size of the inoculated plants regardless of fertiliser and lime treatment. This indicates that the rhizobia that inoculate Caucasian clover is not present in the soil at Lake Heron Station (Clent Hills site).

Conclusion

From the results of the pot experiment (Exp. 3), it appears that the N deficiency of Caucasian clover, which resulted in impeded establishment in Experiment 2, was a result of ineffective inoculation, and possibly Al toxicity issues.

Further details on all three experiments can be found in the research paper to be presented at the 2014 NZGA Conference in November (Appendix 2.3).

Plate 3.9 Glasshouse experiment to test the effectiveness of the commercial inoculant CC283b on Caucasian clover plants grown in soil from Clent Hills on Lake Heron Station. Plants in (a) were inoculated, and plants in (b) were not inoculated.

APPENDICES

Appendix 1 – PhD 18th Month Report

on

Overcoming soil acidity and Aluminium (Al^{3+}) toxicity constraints to legume production in high country pastures

by

Travis P. Ryan-Salter
9 July 2014

Supervisor: Dr. Alistair Black
Co-Supervisors: Dr. Derrick Moot
Dr. Mitchell Andrews
Advisor: Dr. Jim Moir

Lincoln University
Te Whare Wānaka o Aoraki
Faculty of Agriculture and Life Science

Introduction

The New Zealand Merino sheep industry is relatively small, accounting for only 4.7% of New Zealand's total wool production (Te-Ara, 2012). Yet it has a production history stretching back over the last 150 years and todays New Zealand Merino producers are a leading source of fine wool for global markets. Following the tradition of the early pastoral run-holders, the majority of New Zealand Merinos are raised on a pasture-based system, generally comprised of native grasses (mostly tussocks) and introduced grasses, clovers, and herbs; primarily in the 'high country' of New Zealand's South Island. This system is perfectly acceptable for producing fine Merino wool of 12-24 micron and market weight lambs of 30-35 kg within 4-5 months after lambing. However, as global industry competitors in fine wool and lamb production, New Zealand Merino farmers face will be challenged with the goal of improving efficiency and productivity. This challenge can be met, at least in part, by the introduction of forage species to the pasture mix with the potential to increase liveweight gain (LWG) and wool production, increasing the efficiency and productivity of New Zealand Merino farms.

There are some common limitations in the current system which, when remedied by the introduction of different forages, have the potential to substantially increase LWG and wool production. Two of the main problems faced by producers are the inherent temperature and moisture constraints on pasture production in the high country. Therefore, the first obstacles that any proposed forage variety will have to overcome are those of cold, long winters and dry, warm summers. The second main characteristic is that it must be seasonally available when the conventional native pastures and developed grass-based pastures are at their least productive. Finally, the forage variety will need to produce herbage with a high nutritional value. Assuming these conditions are met, an increase in voluntary feed intake by Merino sheep can be expected. With that in mind, there are two forage species that sufficiently meet these conditions: lucerne (*Medicago sativa* L.) and perennial or Russell lupin (*Lupinus polyphyllus* L.).

Lucerne is the least novel of the two forage varieties, having already been identified as a productive forage variety for increasing LWG and wool production on high country properties (Stevens *et al.*, 2012). Lucerne is a perennial, tap-rooted legume, which has been identified as having a greater water use efficiency (WUE) than pure grass and grass/clover swards (Moot *et al.*, 2008). Lucerne is most productive in late spring and early summer (Brown and Moot, 2004), which coincides with the intake pattern of lactating Merino ewes and growing lambs. However, the use of lucerne as a specialist forage on high country properties is limited by its sensitivity to soluble aluminium (> 3 meq/kg) in acidic soils (pH < 5.5) (Moir and Moot, 2010a). These soils are common across large areas of the South Island high country. Soil acidity and high Al can be overcome by either liming where economically feasible, or through the use of alternative forage varieties that are more tolerant of acid soils such as Russell lupin.

Russell lupin is a similar legume to lucerne in that it has a tap-root, and grows from a crown (Scott, 1989a). Its ability to survive and thrive on acidic, low fertility soils in the South Island high country is supported by about three decades of field research at the Mt John research station near Tekapo in the Mackenzie Basin (Scott, 1989b, 1989a; Scott *et al.*, 1995; Scott, 2012). Scott *et al*. (1995) reviewed the applicability of lupins to high country grazing areas in a comparison with other species, and concluded that Russell lupin was the most suitable forage for loose-textured soils that receive low amounts of superphosphate (0-9-0-12), in the moderate to high rainfall areas, or seepage and streamside areas of dry zones. The review also recognised the potential of Russell lupin either as a general purpose species that could be over-sown on undeveloped grassland, or more recently as a 'special purpose' forage option in more developed pastures. However, in reviewing all of the available literature on Russell lupin in New Zealand, it became clear that our current knowledge of lupin as low-input forage variety for Merino production was limited. In particular, its seasonal pattern of dry matter production, nutritive value and acceptability by livestock, and most importantly the LWG and wool characteristics of Merinos grazing on lupins have not been adequately quantified on Merino farms in the high country.

For most legumes, successful growth on marginal soils results from the formation of a symbiotic relationship, in the form of specialised root structures called nodules, with free living, soil inhabiting bacteria, known as rhizobia. This ability mitigates nitrogen (N) deficiency within the plant and alleviates the plant of soil mineral N reliance (Sprent, 2009). When an effective relationship is formed between a host plant and its respective N fixing bacteria, atmospheric N_2 is fixed via the nitrogenase pathway, which is then assimilated by the plant into both shoot and root tissues (Oono and Denison, 2010; Andrews *et al.*, 2011b). Inhabitation of low fertility roadside soils was central to realising the potential of *L. polyphylluss,* and its respective rhizobial symbionts, to survive and thrive in areas traditionally dominated by non-leguminous weed and grass species. Commercial inoculants have been developed for annual species of lupin (e.g. lupinus angustifolius), and have also been recommended as the appropriate inoculant for perennial species. Specifically, inoculant strain NZP2141 was recommended by Scott (1989a), which contains rhizobia belonging to the Bradyrhizobium genera. Bradyrhizobium have been recognised as the main symbiont partner to lupins (Roughley *et al.*, 1993; Jarabo-Lorenzo *et al.*, 2003a) and many other legumes within New Zealand (Weir *et al.*, 2004a; Tan *et al.*, 2013). However, strain type has had little previous quantification for perennial lupins. It is hoped that 'elite' strains, selected based on yield in marginal soils, will have an improved efficiency of nitrogenase production which will result in growth benefits for agricultural plantings.

It is a general phenomenon of grassland development for fine rooted grasses to replace coarsely rooted legumes as the latter build soil N levels. However, legume monocultures (most commonly lucerne) lack a non-leguminous grass which assimilates N solely from the soil, and as a result soil N levels may accumulate to excess levels. There is a risk that accumulated nitrate can then be leached from the soil profile, having adverse impacts on the environment (Ryden *et al.*, 1984; Addiscott, 1996; Di and Cameron, 2002). However, the rate at which legumes assimilate soil N, in response to increasing soil nitrate levels, is largely unknown. The relationship between soil nitrate-N and nitrogen derived from fixation (%Ndfa) was investigated by Armstrong *et al.* (1999) in Australia. That experiment showed that soil nitrate-N levels of >40 kg/ha reduced nitrogen fixation significantly (%Ndfa = <20% plant N) for four legumes. In contrast, Drake (2011) found that %Ndfa of gorse (*Ulex europaeus*) showed little response to increasing soil nitrate level. Lack of knowledge around the nitrogen assimilation of temperate legumes (e.g. *L. polyphyllus* and lucerne) necessitates further research.

As mentioned previously, many farmed high country soils suffer from acidity, and toxic levels of soluble Al. (>3 me/100g). Soils of North Canterbury and Omarama basin were shown to have toxic soluble Al. levels in Moir and Moot (2010b) and Espie (2009), respectively. For both soils, soluble Al. was most prominent at depths of 10 – 30 cm. To offset this effect, and improve legume establishment/persistence, lime must be applied (Davis, 1981; Butler, 1993; Slattery *et al.*, 1995; Caddel *et al.*, 2004; Chan *et al.*, 2007; Moir and Moot, 2010b). However, the rate at which lime moves through the soil is slow (10 – 15 years) (Metzger, 1934; Brown and Munsell, 1938; White, 1967) and some high country sites may require substantial amounts (> 4 t/ha/yr) to correct and maintain acid soils. Introduction of lime directly to subsoil layers may ameliorate this acidity and Al. toxicity (Doss *et al.*, 1979; Cassel, 1980; Anderson and Hendrick, 1983; Farina and Channon, 1988; Hall and Lemon, 2010), and improve the establishment/persistence of tap-rooted legumes (Doss *et al.*, 1979). Results of Rechcigl *et al.* (1991) showed that subsurface application of lime and P significantly improved the biomass productivity of lucerne. In these experiments, subsurface lime application was achieved by modifying a chisel blade or subsoiler for the transport of lime into subsoil layers. The development of a similar implement could prove to be useful at amending subsoil acidity in the South Island high country of New Zealand. Reducing the toxic effects of subsoil Al. may substantially increase the productivity of these areas (Douglas, 1986) and improve the effectiveness of nutrient uptake from subsoil layers, thus reducing the risk of leaching (Espie, 2009).

Therefore, the aim of this thesis is to provide a comprehensive evaluation of perennial lupins as a low-cost forage for high country grazing systems whilst exploring alternative solutions to current production constraints.

Proposed Timetable (Taken from PhD Proposal)

Table **Error! No text of specified style in document.**.1: Timeline of proposed research.

Field and laboratory experiments will take place from February 2013 to March 2015. The majority of data analysis and writing will take place between March 2015 and February 2016.

	2013											2014												2015												2016
Part 1	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J
Proposal	X	X	X	X																																
Literature Review		X	X	X	X	X																														
Machinery Construction				X	X	X	X																													
Part 2																																				
Objective 1		X	X	X	X	X	X	X	X	X			X	X	X	X	X																			
Objective 2				X			X	X	X	X	X	X	X	X	X	X			X	X	X	X	X	X	X											
Objective 3				X				X	X	X	X	X	X	X	X	X			X	X	X	X	X	X	X											
Objective 4									X	X	X	X	X	X	X	X			X	X	X	X	X	X	X											
Part 3																																				
Data Analysis						X						X	X			X	X	X	X					X	X	X	X	X	X							
Writing					X	X	X	X								X	X	X	X	X					X	X	X	X	X	X	X	X	X	X	X	X

Thesis structure and progress to date (%)

Chapter 1 – General Introduction

Writing	50%

Chapter 2 – Review of Literature

Writing	55%

Chapter 3 - Merino Performance and seasonal productivity of a lupin pasture at Sawdon Station

Data Collection	95%
Data Analysis	60%
Writing	60%

Chapter 4 - Characterisation and effectiveness of rhizobia that nodulate lupin

Data Collection	85%
Data Analysis	60%
Writing	35%

Chapter 5 – Nitrogen assimilation of perennial lupin and lucerne

Data Collection	10%
Data Analysis	0%
Writing	5%

Chapter 7 – Animal performance on grazed lupin/cocksfoot pastures compare with lucerne

Data Collection	30%
Data Analysis	0%
Writing	10%

Chapter 8 – Effect of subsurface lime application on the growth of lucerne in acidic soils

Data Collection	40%
Data Analysis	0%
Writing	20%

Chapter 9 – General Discussion

Writing	0%

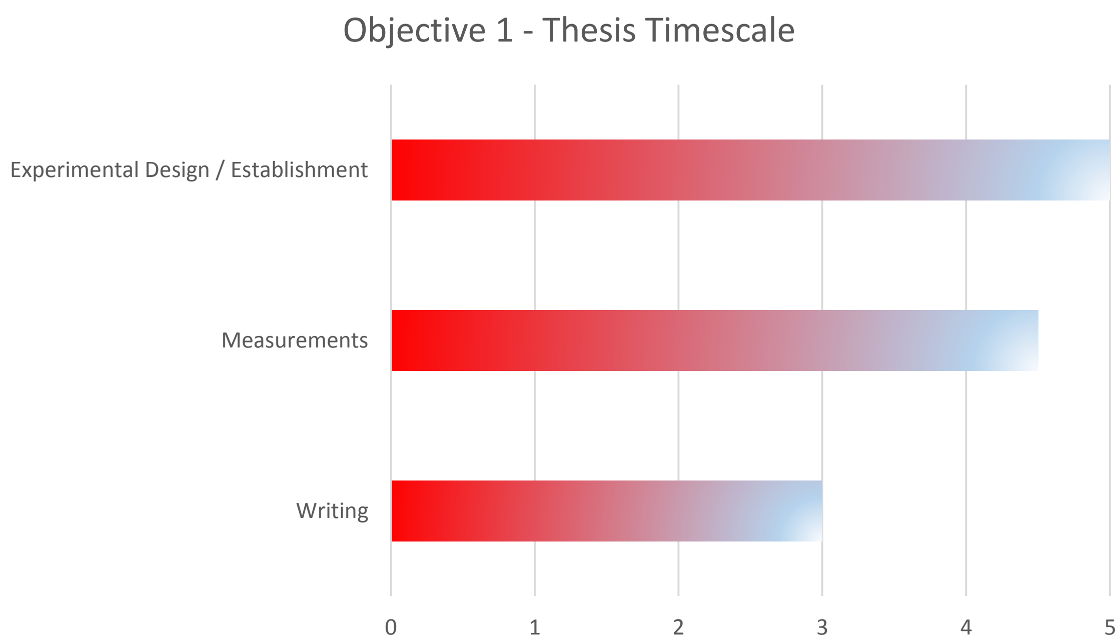
Objective 1 – Merino Performance and seasonal productivity of a lupin pasture at Sawdon Station.

Goals

- Quantify the seasonal production of an established lupin stand.
- Compare animal performance between merino ewes/lambs grazing the lupin stand with those grazing a control pasture.
- Evaluate the forage quality of different components of lupin yield.

Completion of goals to date

Measurements of lupin productivity at Sawdon Station have been completed after two full seasons (2012/13 and 2013/14) of biomass, forage quality and animal performance assessments. A paper titled "*Sheep performance on perennial lupins at Sawdon Station*" has been submitted for publication in the 2014 proceedings of the New Zealand Grassland Association and is attached below.



Conclusions

This study has shown that Russell lupins can provide high quality forage for Merino ewes and lambs on dryland properties in the Mackenzie Basin. The specific conclusions from the study were:

1. Russell lupins survive and thrive on marginal, acidic, low fertility soils in the South Island high country. They are a suitable forage variety for loose-textured soils that receive low amounts of sulphur superphosphate in the moderate-to-high rainfall areas.

2. At Sawdon Station, in the Mackenzie Basin, Merino ewes and lambs on a 10-year-old stand of Russell lupins grew nearly as well as those on conventional lucerne and other pasture varieties. Wool characteristics and lambing and scanning percentages were also similar between the Russell lupins and the conventional pastures.

3. The crop of Russell lupins produced sufficient amounts of forage for the Merino ewes and lambs during the critical period from lambing in October to weaning in February, and for the ewes during flushing from March to May. The total biomass of the crop ranged from an average of 2700 kg DM/ha in October to 7200 kg DM/ha in December, and proportions of leaf, petiole, stem, flower and dead fractions of the lupins all changed throughout the growing season. However, the ewes and lambs appeared to consume more of the green leaves, petioles and flowers of the lupins than the reproductive stems and dead material.

4. The nutritive values (N%, C%, DMD%, ADF% and WSC%) of the Russell lupins differed between the aboveground components of the plants and also varied throughout the growing season. The leaves of the lupins were consistently highest in N (3.4-5.4%) and DMD (81%) which helps to explain the apparent preference for the leaves of the Russell lupins by the Merinos.

Merino ewes and lambs grazing the lupin stand on 14^{th} December 2012 at Sawdon Station.

Sheep performance on perennial lupins over three years at Sawdon Station, Tekapo

A.D. BLACK[1], G. LOXTON[2], T.P. RYAN-SALTER[1] and D.J. MOOT[1]

[1]*Department of Agricultural Sciences, Lincoln University, Canterbury*

[2]*Sawdon Station, PO Box 9, Lake Tekapo, Canterbury*

alistair.black@lincoln.ac.nz

Abstract

Perennial lupin was the dominant species in an 11-year-old pasture at Sawdon Station, Tekapo. Merino ewes grazing on the pasture over the last 3 years were compared to a control group on lucerne. At tailing (December), lambing percentages were 103–120 v 93–117%, lambs averaged 19–20 v 17–21 kg and ewes averaged 58–61 v 61–69 kg. At weaning (February), lambs were 28–30 v 30–31 kg and ewes were 53–62 v 60–65 kg. Between March and mating in May, ewes gained 2–7 v 3–9 kg. At shearing (September), fleeces were 4.62 kg and 18.6 µm v 4.92 kg and 18.5 µm. Average lupin pasture mass reached 7.5 t DM/ha in December. Lupin leaves were 3.8–5.4% N and 80% *in vitro* digestibility. Results support the use of perennial lupins where lucerne fails to thrive in New Zealand high country.

Keywords: liveweight gain, *Lupinus polyphyllus*, Merino, Russell lupin

Introduction

The perennial lupin *Lupinus polyphyllus* has been shown to have potential as a pasture legume in high country environments in New Zealand (Scott, 2001). It can thrive and fix atmospheric nitrogen (N_2) in soils throughout the high country of the South Island, even where aluminium (Al) is toxic for most clovers (*Trifolium* species) and particularly lucerne (*Medicago sativa*)(Moot and Pollock, 2014; Ryan-Salter *et al.*, 2014). However, limited attempts have been made to quantify the livestock performance (Scott *et al.*, 1994) and feed values (Kitessa *et al.*, 1993) of perennial lupin, with an indication that it has only moderate sheep acceptability, due to its alkaloid content, but sheep adapt to it (Scott, 2014).

Sawdon Station, near Tekapo, is one of a few farms in the Mackenzie Basin of the South Island that has been using perennial lupins as a low cost approach to pasture development for the production of fine Merino wool and lambs. The soil on the 7100 ha property is mostly loose-textured and the farm experiences around 140 frosts a year, limiting the options of suitable forage species. The idea of using perennial lupin on the farm was based on its ability to tolerate frosts and start growth early in spring, and to survive and fix N for associated grasses with only 600–650 mm of annual rainfall and modest inputs of fertiliser. Over the last decade, lupin-clover-grass mixes have been established on Sawdon on a commercial scale using the farm's own lupin seed and seed sourced from mid-Canterbury.

The objectives of this study were to 1) compare the performance of Merino ewes and lambs grazing on perennial lupins with those on lucerne and clover-based pastures at Sawdon Station, and 2) characterise the seasonal pattern of herbage mass, composition and nutritional value of the lupins as indicators of sheep performance.

Methods

Lupin pasture

The trial used a 10 ha pasture of perennial lupins at Sawdon, on a flat lower terrace on the northwest side of Edward Stream, 6.3 km south of Tekapo (44°03'54"S, 170°29'22"E). The site is 680 m above sea level and the annual rainfall is estimated to be 600–650 mm. The soil is classified as a sandy loam Ashburton Fluvial Raw Soil.

The pasture was planted in October 2003 after the area had been fallowed over winter and sprayed with glyphosate. A low sowing rate of 3 kg of perennial lupins/ha was used in a seed mix that also contained oats, barley, Italian ryegrass and white clover. The seed mix was broadcast with 200 kg/ha of Cropzeal (20% N, 10% P and 12% S) and incorporated into the topsoil using a Maxi-till. In the first season, the lupin plants were allowed to flower and set seed before grazing. In 2004, the pasture was harvested for silage. Over the following years it was grazed leniently to allow the lupin plants to strengthen and set more seed. In 2010, the lupins were harvested for seed (~400 kg), and in 2011 the pasture was fenced into five similar-sized plots for this grazing trial.

While other lupin-clover-grass mixes on the farm receive modest fertiliser inputs, the much smaller 10 ha trial pasture had been fertilised annually with 200–250 kg/ha of superphosphate (9% P, 11% S) with or without elemental S, and in 2013 it was dressed with 200 kg/ha of a lime (20%), superphosphate (40%), elemental S (40%) and molybdenum (Mo) mix. A soil test in 2011 showed pH, P and S were optimal and Al was low (Table 1).

Grazing management

On 12 December, 2011, 143 two-tooth Merino ewes and their 114 lambs were put onto the lupin plots (14.3 ewes/ha) and compared with a control group of similar animals on lucerne and, occasionally, clover-based pastures (hereon this treatment is sometimes referred to as 'lucerne'). At weaning on 10 February, the ewes and lambs were taken off the lupins to allow recovery of herbage mass. Six weeks later on 23 March, 120 of the same ewes were run back onto the lupins to determine if lupins could be used for flushing and mating (12 ewes/ha). Rams went out on 18 May and the group was taken off the lupins on 20 June. All ewes were shorn in September, 2012. The lupin plots were rotationally grazed with 2-week shifts during both summer and autumn grazing periods.

A longer trial was started on 11 October, 2012, when the 120 pregnant ewes were set stocked on four lupin plots at 16 ewes/ha. Again the ewes were compared with a control group on lucerne. Between tailing on 14 December and weaning on 18 February, the ewes and lambs were rotated around all five plots (12 ewes/ha) with fortnightly shifts. After a 1-month spell off lupins, 103 of those ewes were tagged on 18 March and started to rotationally graze around all the lupin plots (10 ewes/ha), again with 2-week shifts. Rams joined the ewes on 20 May and all sheep were taken off the lupins on 20 June. Seventy-five control ewes were also tagged on 18 March and grazed on lucerne and clover-based pastures through to the end of mating. All ewes were shorn on 19 September, 2013.

On 10 October, 2013, 101 of the tagged lupin ewes were set stocked on four plots (13.5 ewes/ha) for lambing. Between tailing on 16 December weaning on 19 February, the group was rotationally grazed on all five plots (10 ewes/ha, 2-3-week shifts). At weaning, the lambs were taken off the trial and the ewes returned to rotationally graze on all lupin plots until 27 March. Again after a 1-month spell for crutching, 94 of the ewes were put back onto the lupins on 24 April to rotationally graze all plots (9 ewes/ha). They were joined by a ram on 19 May. The control group was again on lucerne and sometimes clover-based pastures.

Measurements

All ewes on the lupins and a sample of at least 50 ewes on the control pastures were weighed in October, at tailing in December and weaning in February, and in March or April and May. All lambs on the lupins and at least 50 lambs on the control pastures were also weighed at tailing and weaning. Lambing percentage was obtained at tailing as the number of lambs tailed relative to the number of ewes in the group.

At shearing on 19 September, 2013, the fleece weight, staple length and mean fibre diameter (“micron”) of the ewes that were on the lupins during the previous two seasons were compared with ewes that had been on the control pastures. Staple length and micron of mid-side samples were examined using a Fibrescan analyser (Eugene O’Sullivan, Pasture Measurements Ltd, Timaru).

Herbage mass, composition and nutritive value of the lupins were measured at monthly intervals during the second and third growth seasons. A 3–5 m by 1.15 m strip was cut at three random points across each plot to a height of 4–5 cm using a sickle mower. The cut herbage was weighed fresh and samples were taken back to Lincoln University. Here, 200–500 g was dried at 65°C to calculate the dry matter (DM) percentage to determine herbage mass, and another 200–500 g separated and dried to estimate composition.

N content of 129 samples of lupin, collected in the second season, was analysed to determine using a Variomax CN analyser, and *in vitro* dry matter digestibility (DMD) was analysed following the pepsin-cellulase assay. Samples included the separated leaves, petioles, stems, flowers plus green seed pods and dead material of lupin, which had been oven-dried and ground to pass through a sieve with 1 mm pores.

Significant (α=0.05) differences in live weight and wool characteristics between the lupin and control groups, for the dates when individual animal data were obtained, were tested by one-way analysis of variance in Genstat 16 statistical software.

Results

At weaning on 10 February, 2012, the lambs on the lupins averaged 28 kg (n=114) and had gained 150 g/day since tailing on 12 December, while the lambs on the lucerne averaged 31 kg and gained 217 g/day (Figure 1). The ewes on the lupins lost an average of 3 kg over the two-month summer period while the ewes on lucerne gained 5 kg. Between 23 March and 18 May, the ewes on the lupins gained 7 kg (125 g/day) and the ewes on the lucerne gained 9 kg (161 g/day).

At tailing on 14 December, 2012, the lambing percentage on the lupins was 103% compared with 93% on the lucerne, and the lambs averaged 20 and 21 kg respectively (Figure 1). The ewes on the lupins lost 8 kg during lambing while the ewes on the lucerne lost 2 kg. At weaning on 18 February, the lambs on the lupins again averaged 28 kg (n=120) and had gained 121 g/day since tailing while the lambs on the lucerne averaged 31 kg and gained 152 g/day. The ewes on the lupins maintained weight over the summer period while the ewes on the lucerne gained 3 kg. Between 11 April and 22 May, the lupin ewes gained 2.6 kg (64 g/day) and the lucerne ewes gained 4.9 kg (120 g/day).

At tailing on 16 December, 2013, the lambing percentages on the lupins and lucerne were 120% and 117%, and the lambs averaged 19 and 17 kg, respectively (Figure 1). The ewes on the lupins lost 4.3 kg during lambing whereas the ewes on lucerne gained 4.0 kg. At weaning on 19 February, the lambs on both treatments averaged 30 kg (n=100) after they had gained 166 g/day on the lupins and 194 g/day on the lucerne since tailing. The ewes on the lupins gained

1.3 kg while the ewes on the lucerne lost 3.6 kg. Between 24 April and 19 May, the ewes on the lupins gained 1.7 kg (63 g/day) and the ewes on lucerne gained 2.6 kg (96 g/day).

At shearing on 19 September, 2013, the fleece weight of the ewes that had been on the lupins during the previous two growth seasons was an average of 4.64 kg compared with 4.92 kg ($P<0.01$) for the ewes that had been on the lucerne and other improved pastures. Staple length and mean fibre diameter were similar ($P=0.373$ and 0.664) at 80 mm and 18.5 μm (Table 2).

In October, 2012, the lupin plots had an average herbage mass of 2.7 t DM/ha, which increased to a maximum of 7.2 t DM/ha at tailing in December before decreasing to 5.8 t DM/ha at weaning in February (Figure 2). After a 1-month spell the ewes were put back onto an average of 6.2 t DM/ha in March which decreased to 4.1 t DM/ha by May, 2013. The herbage mass in October was 41% lupin leaf and petiole, 1% stem, 51% dead (mostly lupin stem from the previous year) and 7% other species. This changed to 42% leaf and petiole, 35% stem, 7% lupin flower, 8% dead and 9% other species in December. By February it was 24% leaf and petiole, 36% stem, 1% flower, 10% dead and 29% other species. Green lupin decreased and dead stem increased over the 2-month autumn grazing period to the extent that most of the herbage on offer in May was dead stem.

On 19 September, 2013, the average herbage mass over the lupin plots was 1.9 t DM/ha, which increased to a maximum of 8.3 t DM/ha in December, but then decreased to 2.9 t DM/ha in March, when the ewes were taken off the lupins (Figure 2). After the 1-month spell the ewes were returned to an average herbage mass of 3.2 t DM/ha in April which decreased to 2.9 t DM/ha by May, 2014. The herbage in September was 40% leaf and petiole, 58% dead stem and 2% other species in September, which changed to 37% leaf and petiole, 35% stem, 12% flower, 13% dead material and 3% other species in December. By April it was 22% leaf and petiole, 1% green stem and 73% dead (mostly stem), and by May 4% was leaf and petiole and 87% was dead.

N% was highest in the leaves and flowers plus green seed pods of the lupins and lowest in the petioles, stems and dead fractions (Figure 3). Leaf N decreased over the growth season from 5.4% to 3.8%, petiole N decreased from 3.1% to about 1.5%, stem N dropped from 4.3% to a minimum of 0.7% and then increased to 1.8%, and N content of dead material was always between 0.6 and 1.7%.

DMD of leaves, petioles and stems was 80% in October, and leaf DMD stayed at 80% over the rest of the growth season, while petioles and flowers plus seed pods decreased to 60–70%, stems to 45–55%, and dead material was 30–56% (Figure 4).

Discussion

The stand of perennial lupins used in this trial had survived under sheep grazing, modest inputs of fertiliser and lime, and 600–650 mm of rain a year, for 8 years prior to commencing measurements. This result and previous high country research (Scott, 1989a; Scott *et al.*, 1994) meant we were confident that Merinos would graze on the lupins and the plants would recover from grazing. However, neither the performance of the Merinos nor the quality of the herbage had been recorded. After 3 years of measurement, we now know Merinos on lupins will perform almost as well as Merinos on lucerne and other improved pastures.

The nature of an on-farm trial means our ability to explain any difference in sheep performance is limited. However, the trial has demonstrated the performance of Merinos grazing on perennial lupins in their environment, where this lupin species will most likely be used. Also, the additional quantification of herbage mass and nutritive value of the lupins has helped explain the animal performance results. The results have been a useful extension vehicle, the focus of a field day and visits by Merino growers and industry partners. Further work is required to clarify the animal results.

With the limitations of on-farm trial conditions in mind, there are three key results that can be discussed. First, perennial lupins were used successfully as a forage crop for lambing (they also provided tall shelter for new-born lambs), lactation and flushing ewes before and during mating, with acceptable lambing percentages, lamb weights (Figure 1) and wool growth (Table 2). The ewes on the lupins did lose 3–8 kg during the lambing/lactation period and gained 2 kg less than the control ewes during autumn (Figure 1). This was possibly because of different stocking rates, feed supply and grazing preferences by the sheep between the different pasture types. However, where lucerne cannot be grown, these results suggest lupin is a viable perennial legume for high country environments.

Second, the lupins started growth in September and provided significant amounts of forage during lambing and lactation under 13.5–16 ewes/ha (Figure 2). The grazing management on the trial limited our ability to measure the yield of the lupin plots, but the plot that was closed during spring yielded ~8.5 t DM/ha by the end of November each year. This compares with a nearby crop of lucerne that yielded 4.5 t DM/ha when it was cut for silage in the same month. Much of the lupin herbage consisted of green and dead stem, but green leaf and petiole, and other palatable species growing between the lupins, were sufficient to support acceptable lamb growth through to February and ewe growth between March and May each year.

Third, the leaves of the lupins were high in crude protein (N% × 6.25) and digestibility during the entire grazing season (Figures 3 and 4), similar to lucerne and clovers. The N and digestibility values were also high in the flowers plus green pods, but decreased in the petioles (leaf stalks) and stems as the plants developed. These results were expected (Kitessa *et al.*, 1993) and help to explain why more leaves and flowers were grazed by the ewes and lambs than green stem and dead material (based on the herbage composition of plots before and after grazing). The sheep also grazed on any palatable companion plants, but they did adapt to the lupins.

The overall results of this trial demonstrate the potential for perennial lupins to be used on-farm. In addition to these results, agronomic data on sowing rates, fertiliser requirements, grazing management, and survival in a range of edaphic and climatic environments are required to develop a comprehensive extension package. However, results to date suggest attaining such data would be worthwhile to provide Merino growers with a low cost, persistent (Scott, 2014) alternative to lucerne.

ACKNOWLEDGEMENTS

The authors are grateful for funding from NZ Merino Company for year 1 of this trial and from Lincoln University for years 2 and 3. We acknowledge the significant contributions made by Denis Fastier, Eugene O'Sullivan, Dick Lucas, Jim Moir, Mart-Marie Roux, Kate Wilson, Catherine Duchaux and Shuang Jiang.

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Table 1 Soil test (0–7.5 cm depth) from the Russell lupin stand at Sawdon Station in 2011.

pH	Olsen P (mg/L)	Sulphate S (mg/kg)	Exch Ca (QTU)	Exch Mg (QTU)	Exch K (QTU)	Exch Na (QTU)	Exch Al (mg/kg)
6.0	24	9	4	25	13	5	<0.5

Figure 1 Liveweight changes of Merino ewes and lambs grazing on perennial lupins compared with lucerne and clover-based pastures (control) on Sawdon Station.

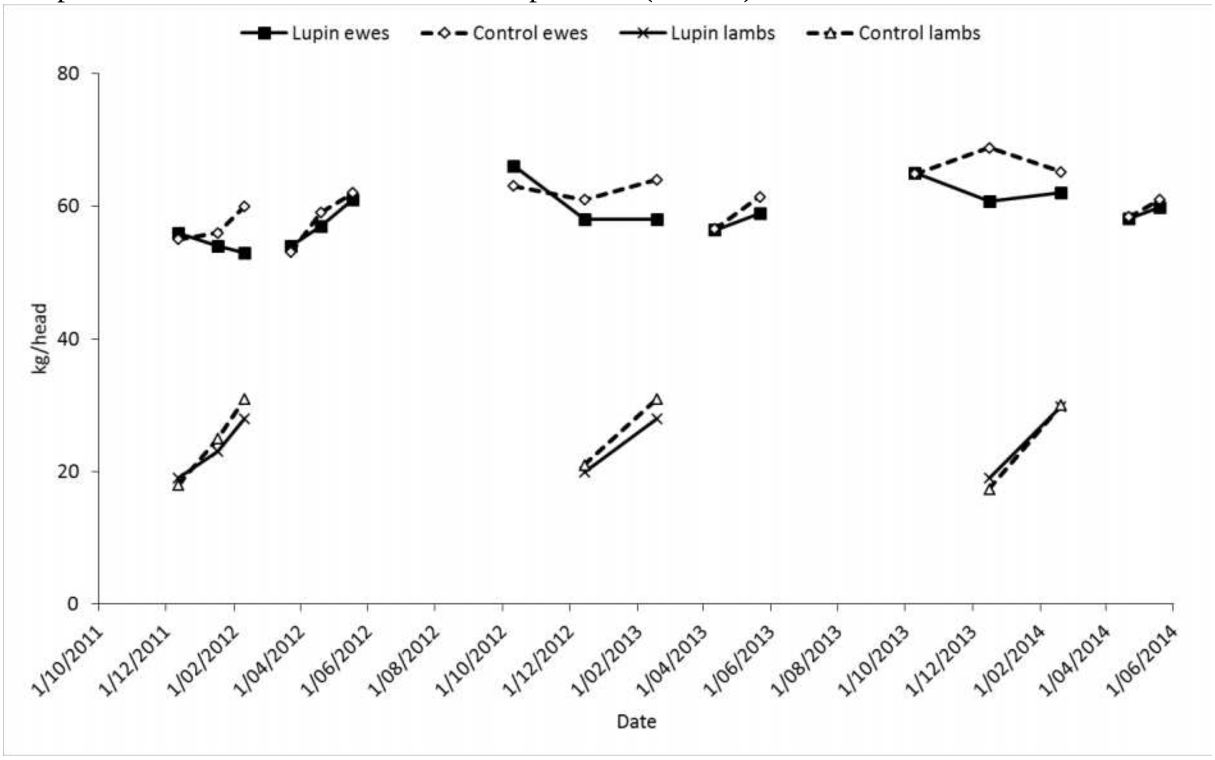


Table 2 Wool characteristics at shearing in September, 2013, of ewes that had been grazing on perennial lupins during the previous two growth seasons compared with ewes that had grazed on lucerne and clover-based pastures (control) at Sawdon Station.

	Lupin	Control	SED	P value
Fleece weight (kg)	4.64	4.92	0.090	0.002
Staple length (mm)	79	80	1.4	0.373
Mean micron (µm)	18.6	18.5	0.21	0.664

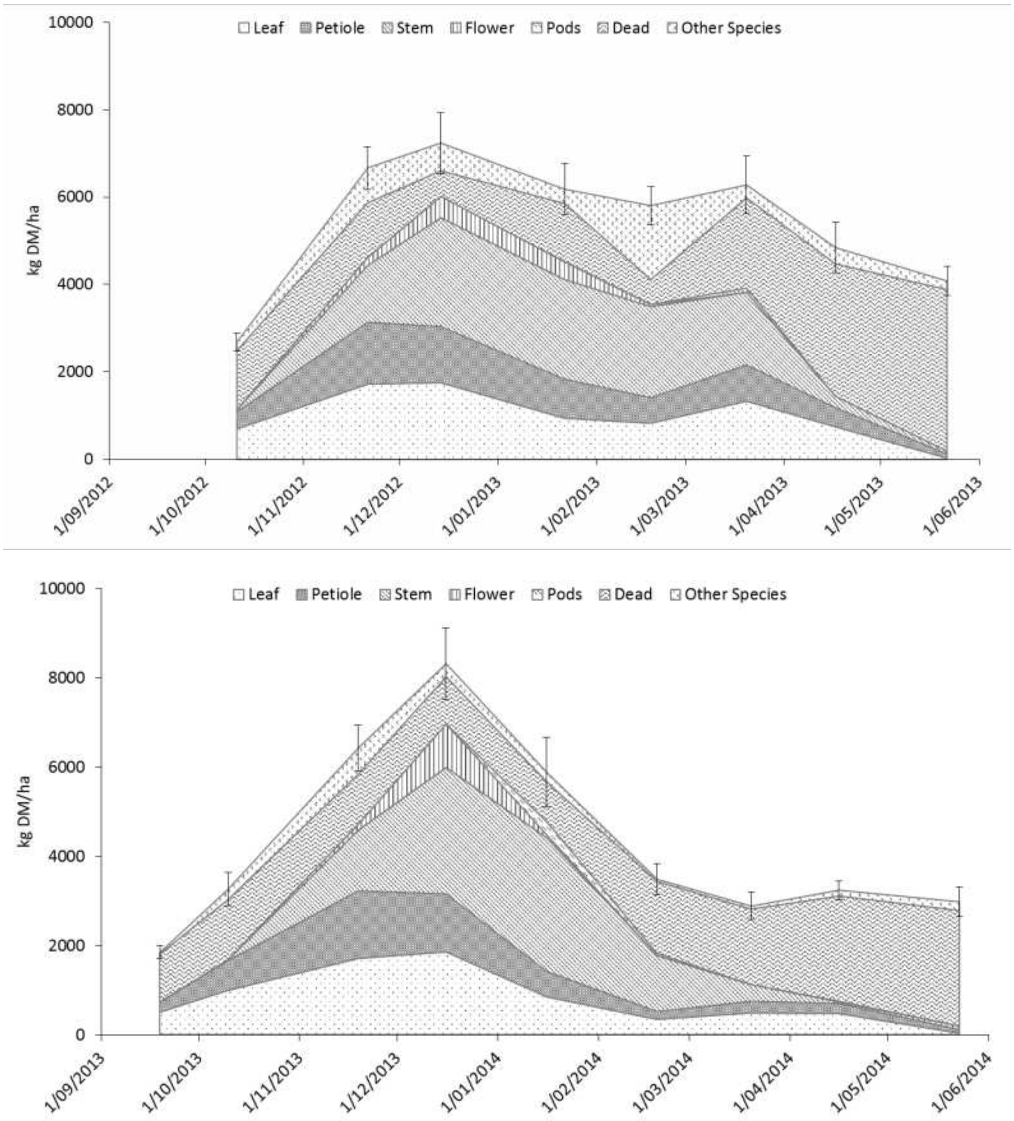


Figure 2 Seasonal pattern of herbage mass and composition of a perennial lupin stand grazed by Merinos on Sawdon Station.

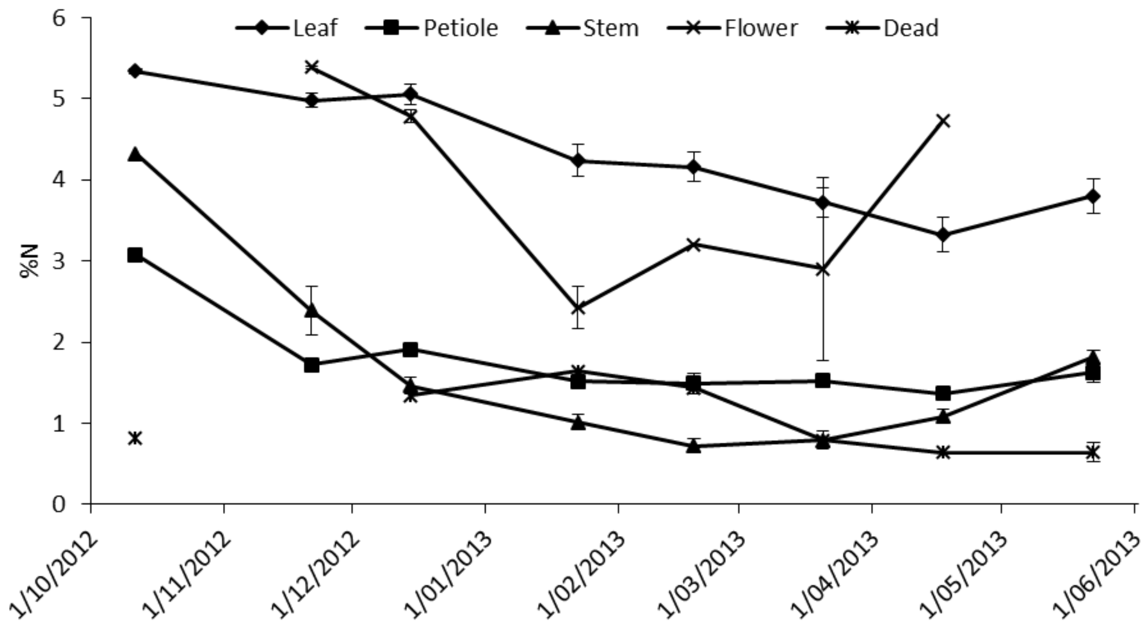


Figure 3 Nitrogen concentrations of perennial lupins on Sawdon Station.

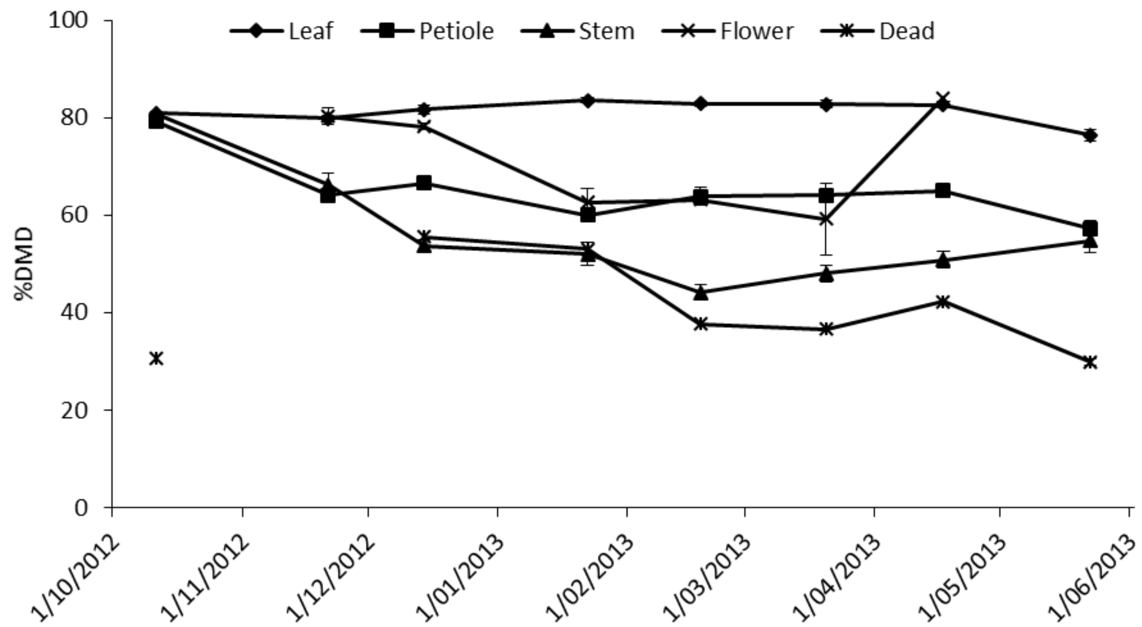


Figure 4 *In vitro* dry matter digestibility of perennial lupins on Sawdon Station.

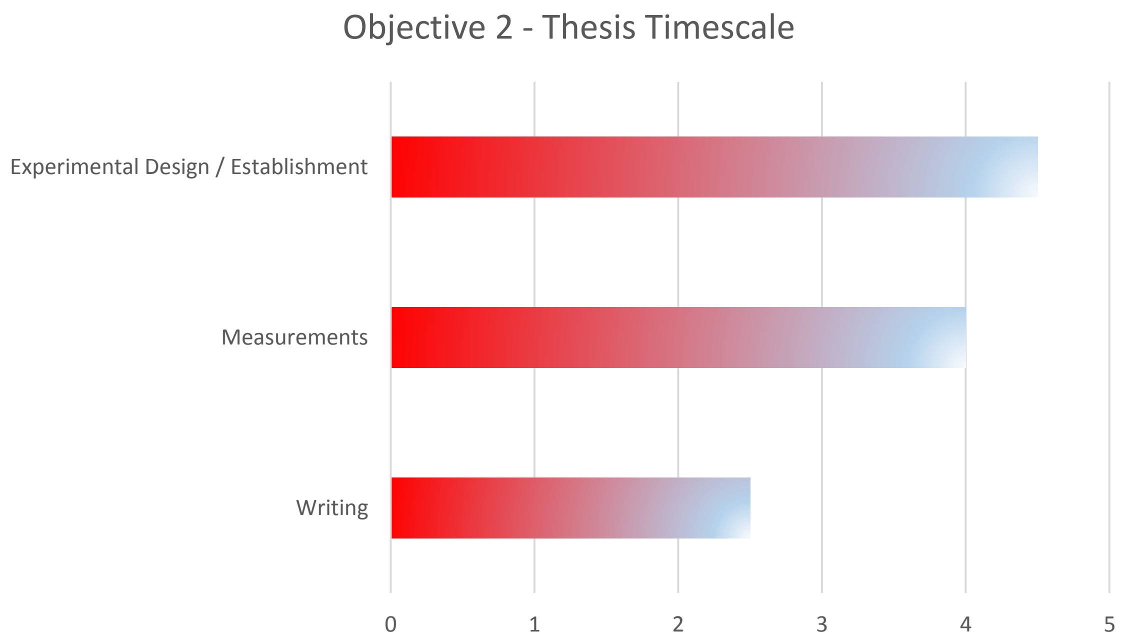
Objective 2 – Characterisation and effectiveness of rhizobia that nodulate lupin.

Goals

- Characterise the rhizobia that nodulate perennial lupin throughout the South Island of New Zealand.
- Compare the 16s rRNA, nifH and nodA genes of each symbiont.
- Compare the symbiotic efficiency of isolated rhizobia strains under glasshouse conditions.

Completion of goals to date

After initial collection of rhizobial isolates from several sites across the South Island; laboratory assessment has confirmed that rhizobia which effectively nodulate perennial lupin are those from the *Bradyrhizobium* genera. For these isolates, full gene sequences have been completed for the 16s rRNA housekeeping gene, nifH gene and the nodA gene. Lupin isolates have been compared with those from other weed species (e.g. gorse) for their phylogenetic similarity and their symbiotic efficiency. A glasshouse experiment was used to test the growth of plants in response to several rhizobial inoculants. Currently, a second glasshouse experiment has been established, and we are awaiting results.



A paper titled "*Identification and effectiveness of rhizobial strains that nodulate Lupinus polyphyllus*" has been submitted for publication in the 2014 Proceedings of the New Zealand Grassland Association, and is presented below.

Identification and effectiveness of rhizobial strains that nodulate *Lupinus polyphyllus*

T.P. RYAN-SALTER, A.D. BLACK, M. ANDREWS and D.J. MOOT
Department of Agricultural Sciences, Lincoln University, Canterbury
travis.ryansalter@lincolnuni.ac.nz

Abstract

Lupinus polyphyllus plants were heavily nodulated at 10 field sites sampled across the South Island. Twenty-two bacterial isolates from these nodules formed functional nodules on *L. polyphyllus* indicating that rhizobia that nodulate *L. polyphyllus* are present across a wide range of sites in the South Island. Gene sequences identified all 22 isolates and the Group G commercial inoculant as *Bradyrhizobium*. Eleven isolates and the Group G inoculant were tested for their effectiveness on growth of *L. polyphyllus* plants in a high country soil in a glasshouse. All plants nodulated regardless of inoculum treatment but there was variability in effectiveness indicating that it may be worthwhile using a rhizobial inoculant on high country soils, but further work is required before a recommendation can be made.

Keywords: nitrogen fixation, perennial lupin, Russell lupin.

Introduction

Wild populations of the perennial legume *Lupinus polyphyllus* have colonised roadsides and riverbeds throughout the South Island of New Zealand. Originally introduced as a horticultural garden species, *L. polyphyllus* and its variants (hybrids of *L. polyphyllus* with several other lupin species; also known as Russell lupins) were valued for their colourful flowers. However, garden escapes and deliberate spreading on bare roadside soils have caused proliferation of the species within the Mackenzie Basin and Arthur's Pass. More recently, *L. polyphyllus* has been shown to have potential as a forage plant in extensive high country grasslands (Black *et al.*, 2014; Scott, 2014).

As with most legumes, *L. polyphyllus* is capable of fixing atmospheric nitrogen (N) via symbiotic bacteria ("rhizobia") in root nodules. This ability can give legumes an advantage under low soil N conditions if other factors are favourable for growth (Andrews *et al.*, 2011a; Andrews *et al.*, 2013). Annual lupin species (e.g. *L. angustifolius*) are generally nodulated by rhizobia strains belonging to the slow-growing, acid-tolerant *Bradyrhizobium* genus (Jarabo-Lorenzo *et al.*, 2003b; Weir *et al.*, 2004b). Commercial inoculants that contain *Bradyrhizobium* sp. have been developed for annual lupins, and have also been recommended for use on *L. polyphyllus* (Scott, 1989a). However, no attempt has been made to select rhizobial strains for use as an inoculum on *L. polyphyllus*.

The objectives of this study were to 1) determine if *L. polyphyllus* is nodulated over a wide range of sites throughout the South Island of New Zealand, 2) genotypically characterise the rhizobia that nodulate *L. polyphyllus* in the South Island, and 3) assess if there is variability in effectiveness of these rhizobia on growth of *L. polyphyllus* in high country soil. This final objective will help determine if use of a commercial inoculant is worthwhile in high country soil.

Methods

Bacterial isolates

Twenty-two rhizobial isolates were obtained from nodules of different *L. polyphyllus* plants sampled from four sites at Arthur's Pass (AP; 11 isolates), three sites in the Mackenzie District (MD; six isolates), two sites in Central Otago (CO; three isolates) and one site near Te Anau (TA; two isolates), South Island, New Zealand in March 2013 (Figure 1). All isolates were obtained from wild populations of *L. polyphyllus* except for two isolates that were obtained from an agricultural stand at Sawdon Station, near Tekapo, in the Mackenzie District. A further isolate was obtained from *L. polyphyllus* plants supplied Group G inoculant, recommended for annual lupins (Becker Underwood), under sterile conditions. Root nodules were surface sterilised by immersion in 96% ethanol for 5 s and 5% sodium hypochlorite for 3 min and then were rinsed with sterile water. Surface-sterilised nodules were crushed in sterile water, and this suspension was streaked onto yeast mannitol agar (YMA) (Vincent, 1970) and incubated at 20°C in the dark for 2–4 days. A purified culture was obtained by repetitive subculture. Samples of all cultures were inoculated into a suspension of yeast mannitol broth (YMB) (Vincent, 1970) and used for preparation of DNA or inoculum.

Gene sequencing and phylogenetic analyses

DNA was extracted from the bacterial cultures using the standard Gentra PUREGENE Purification Kit (Qiagen) following the protocol for gram-negative bacteria. Two genes were sequenced: the small subunit ribosomal RNA (16S rRNA) and N-acyltransferase nodulation protein A (*nodA*). The 16s rRNA and *nodA* primers used were those described in Weisburg *et* *al*. (1991) and Chaintreuil *et al*. (2001) respectively. Both primers were manufactured by Integrated DNA Technologies, Auckland, New Zealand.

All PCR amplifications were performed using the FastStart™ Taq DNA Polymerase kit (Roche Applied Science, Auckland) optimised for annealing temperature and primer concentrations. The PCR products were resolved via gel electrophoresis (1% agarose gel in 1× Tris-acetate-EDTA buffer) followed by staining with ethidium bromide and viewing under UV light. PCR products were sequenced by the Biological Protection Research Centre Sequencing Facility, Lincoln University, and DNA sequence data were obtained via Sequence Scanner v 1.0 software (©Applied Biosystems) and were edited and assembled using DNAMAN Version 6 (©Lynnon Biosoft Corporation).

DNA sequences were aligned and Maximum Likelihood trees constructed with 500 bootstrap replications with partial deletion and 80% coverage cut off using MEGA6 software (Tamura *et al.*, 2007). Only bootstrap values ≥50% are shown for each tree. Type strains of the most closely related *Bradyrhizobium* spp. on the GenBank sequence database (www.ncbi.nlm.nih.gov/genbank) were included in the 16s rRNA and *nodA* trees. *Ensifer meliloti* was used as an out-group on both trees.

Nodulation and N_2 fixation

All isolates were tested for nodulation and N_2 fixation under sterile laboratory conditions. Seeds of *L. polyphyllus* were scarified then surface sterilised in 5% sodium hypochlorite for 15 min, rinsed in deionised water and then germinated on moist germination paper at room temperature in the dark. After germination, seedlings were transferred to polyethylene terephthalate jars (one seedling per jar) containing vermiculite and were supplied with a complete nutrient medium (pH 6.0) as described previously (Tan *et al.*, 2012). Plants were grown in a controlled environment cabinet and exposed to a 16-h photoperiod (400 µmol photons/m^2/s) at a constant 25°C. At planting, seedlings were inoculated with 5 ml of the appropriate rhizobial strain grown to log phase (~1×10^8 cfu/ml). Uninoculated plants supplied with YMB only were used as controls. There were three replicate jars per treatment. At 40–50 days after inoculation, plants were tested for nitrogenase activity using the acetylene reduction assay (Cummings *et al.*, 2009).

Rhizobial effectiveness

Eleven isolates, representative of all 22 strains obtained from *L. polyphyllus*, were tested along with the commercial Group G inoculant for effectiveness on growth of *L. polyphyllus* plants in high country soil in a glasshouse. Germinated *L. polyphyllus* seeds were planted into 1.5 litre pots (two seedlings per pot) containing topsoil from a site at Glenmore Station, Lake Tekapo, with no known history of *L. polyphyllus* or other lupin crops (pH 5.5, Olsen P 14 mg/l, K 0.69 me/100 g, Mg 0.83 me/100 g, and Al 2.5 mg/kg). Plants were inoculated with the appropriate strain at planting and after 24 days. Five replicate pots were used for each strain and an uninoculated control. Pots were watered with tap water when necessary. When seedlings had 2–3 trifoliate leaves, they were thinned to one per pot. Plants were harvested 79 days after sowing, and symbiotic effectiveness assessed by analysis of variance of dry weights using Genstat 16 software.

Results and Discussion

At all 10 field sites (Figure 1), all *L. polyphyllus* plants sampled were heavily nodulated. These nodules were pink inside and assumed to be functional. Twenty-two bacterial isolates obtained from these nodules were shown to form functional nodules on *L. polyphyllus* on inoculation in sterile laboratory conditions (acetylene reduction activity). These results indicate that rhizobia that nodulate *L. polyphyllus* are present across a wide range of sites in the South Island, including the agricultural stand of *L. polyphyllus* at Sawdon Station, Tekapo, which was established using uninoculated seed (Black *et al.*, 2014).

The 16s rRNA and *nodA* gene sequences identified all 22 isolates and the Group G inoculant as *Bradyrhizobium* sp. One isolate (AP11) showed substantially different 16s rRNA and *nodA* sequences from the others and was not included in the phylogenetic trees (Figure 2). The 16s rRNA sequence for this strain showed 97.5% similarity to that of *B. japonicum* isolated from the crop plant *Glycine max* (soya bean) in Japan (Kaneko *et al.*, 2011). Its *nodA* sequence showed 72% similarity to that of *B. cytisi* isolated from *Cytisus villosus* (hairy broom) in the Moroccan Rif (Chahboune *et al.*, 2011). The origin of this isolate is unclear. The other 21 isolates from *L. polyphyllus* clustered together for both 16s rRNA (Figure 2A) and nodA (Figure 2B) gene sequences. The 16s rRNA sequences separated into four groups. Groups 1 and 2 (11 isolates) were most closely related to *B. canariense* (99.58%–99.75% similarity) which was isolated from *Chamaecytisus palmensis* (tree lucerne) in La Laguna (Tenerife), Spain (Vinuesa *et al.*, 2005) and the Group G inoculant (99.00%–99.17%

similarity). Groups 3 and 4 were most closely related to *B. japonicum* (99.57%–99.83% similarity). The *nodA* sequences separated into two major groupings. Two of the strains aligned closest to the isolate from the Group G inoculum, but 19 of the strains clustered together closest to, but clearly separate from (92.89%–96.67% similarity), *B. cytisi* isolated from *C. villosus*.

Thus overall, the DNA sequence data indicate that bradyrhizobia with distinct *nodA* genes are of widespread occurrence in the South Island of New Zealand. The possible sources of these bradyrhizobia are: 1) an inoculant used in New Zealand in the past, 2) a strain from outside New Zealand that has become established with *L. polyphyllus* throughout the South Island, and 3) naturally occurring bradyrhizobia in New Zealand that nodulate *L. polyphyllus*. Further work is required to clarify this point.

In the glasshouse experiment, all *L. polyphyllus* plants were nodulated regardless of inoculum treatment. This result is in agreement with the field study and indicates that rhizobia that nodulate *L. polyphyllus* are present in the agricultural soil tested from Glenmore Station, Lake Tekapo, with no known history of *L. polyphyllus* or other lupin crops. It is also in agreement with Scott (1989a), which stated that *L. polyphyllus* will nodulate in high country soils without inoculum, although it was also indicated that use of rhizobial inoculum could be beneficial. In the glasshouse experiment, there was variability in total plant dry weight across the inoculum treatments (Figure 3). In particular, growth with strain AP5 was greater than that of the control, indicating that there may be potential for selection of an elite strain for use as a rhizobial inoculum. However, this experiment needs to be repeated and carried out for a longer time period before recommendations could be made with regard to use of inoculum on *L. polyphyllus* in high country soils.

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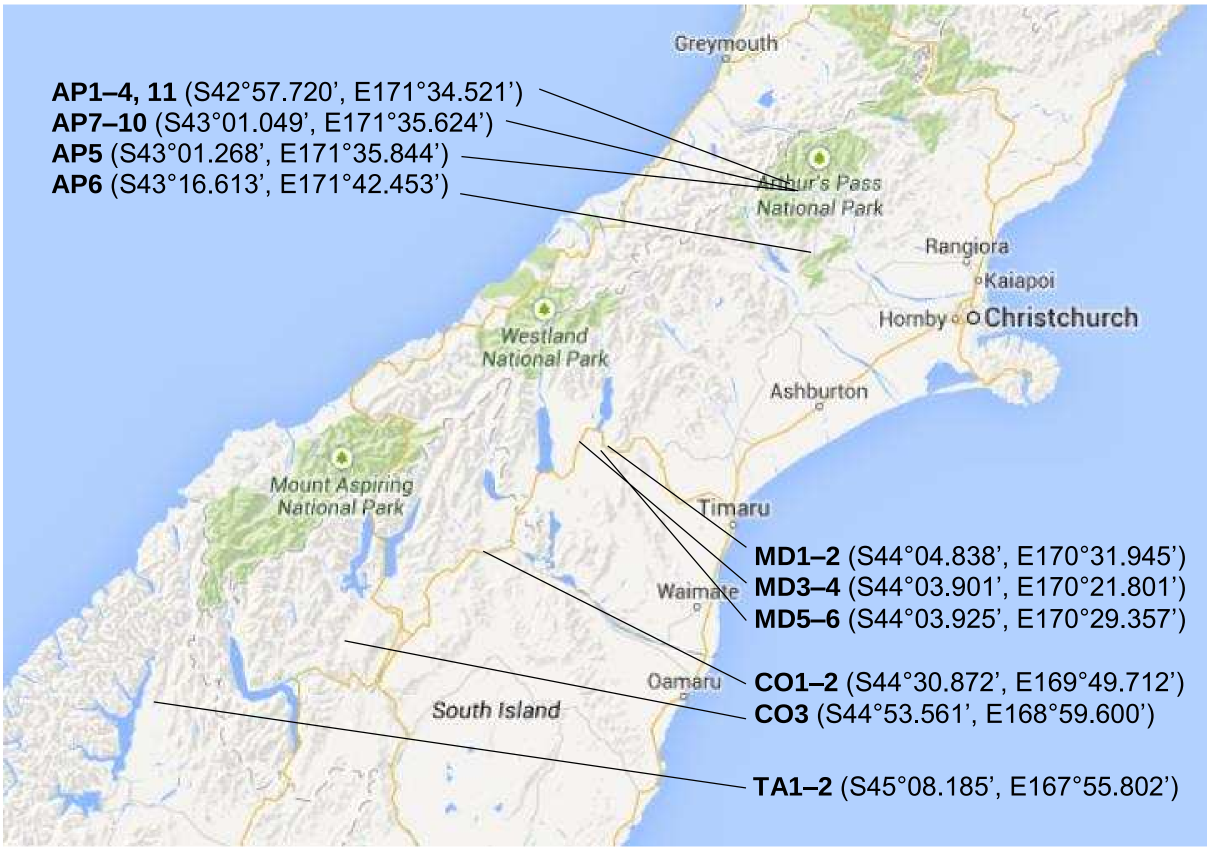


Figure 1 Bacterial isolates were obtained from *Lupinus polyphyllus* at four sites at Arthur's Pass (11 isolates: AP1–11), three sites in the Mackenzie District (six isolates: MD1–6), two sites in Central Otago (three isolates: CO1–3), and one site near Te Anau (two isolates: TA1–2) in March 2013. Plants were sampled from wild populations except at one agricultural site (MD5 and 6) at Sawdon Station near Tekapo in the Mackenzie District.

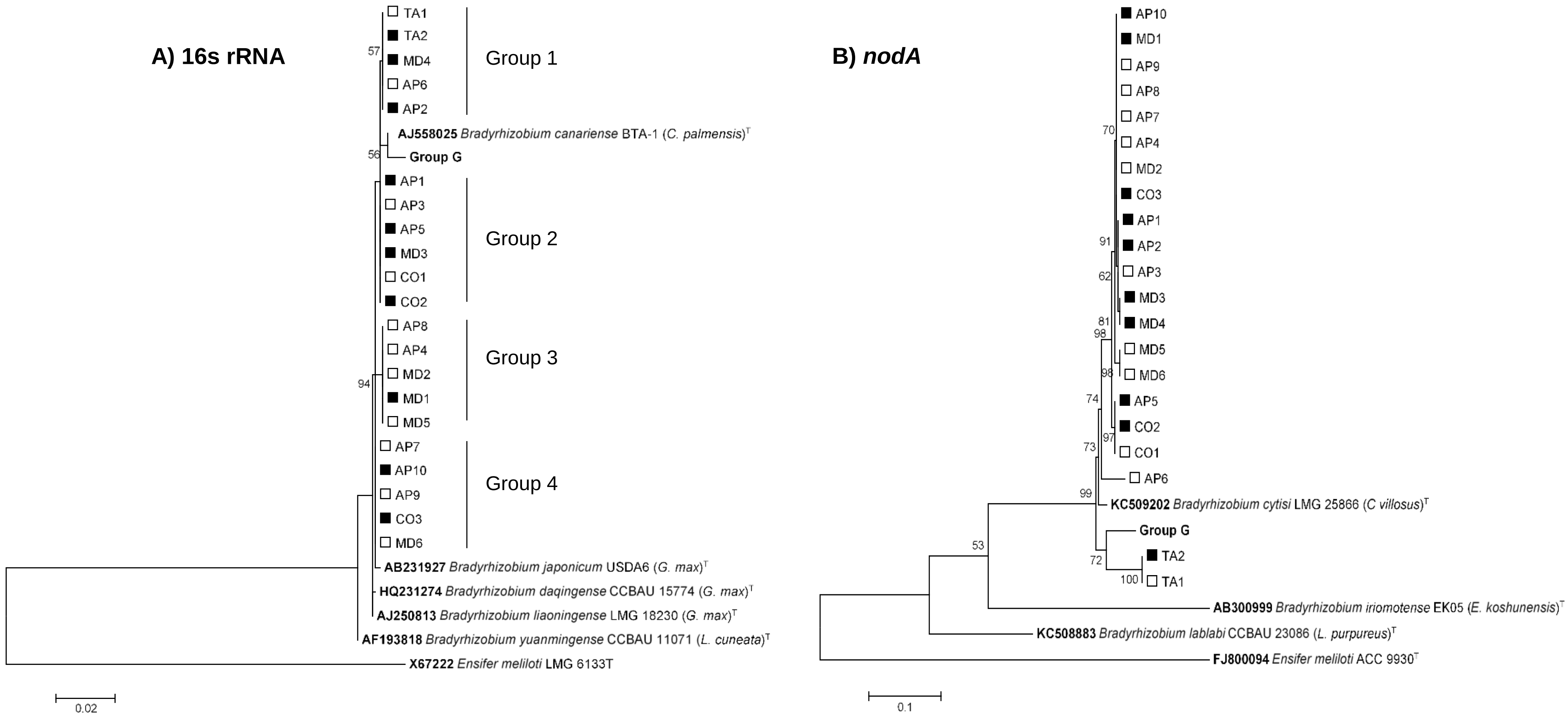


Figure 2 Phylogenetic genetic trees of 16s rRNA (A) and *nodA* (B) gene sequences of 21 bacterial isolates from *Lupinus polyphyllus* sampled in soils at Arthur's Pass (AP1–10), Mackenzie District (MD1–6), Central Otago (CO1–3) and Te Anau (TA1–2) in New Zealand, commercial Group G inoculant currently recommended for use on annual lupins, and selected type strains of *Bradyrhizobium* spp. GenBank accession numbers are in bold and host legume species are in parentheses. *Ensifer meliloti* was used as an out-group. Selected isolates (■) were tested in a glasshouse experiment. Numbers on branches indicate bootstrap % from 500 replicates (shown only when ≥50%).

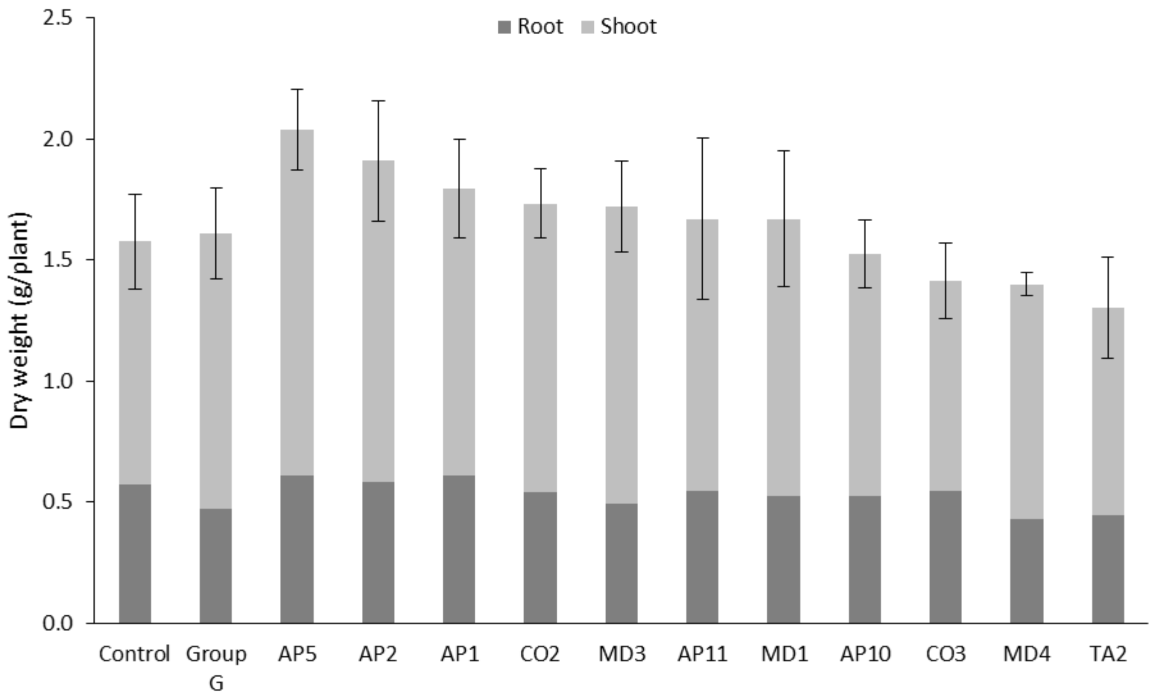


Figure 3 Dry weight of *Lupinus polyphyllus* plants inoculated with 11 bacterial isolates from *L. polyphyllus* sampled in soils at Arthur's Pass (AP), Mackenzie District (MD), Central Otago (CO) and Te Anau (TA) in New Zealand, an isolate from a commercial Group G inoculant currently recommended for use on annual lupins, and an uninoculated control, in high country soil collected from an agricultural site at Glenmore Station, Tekapo.

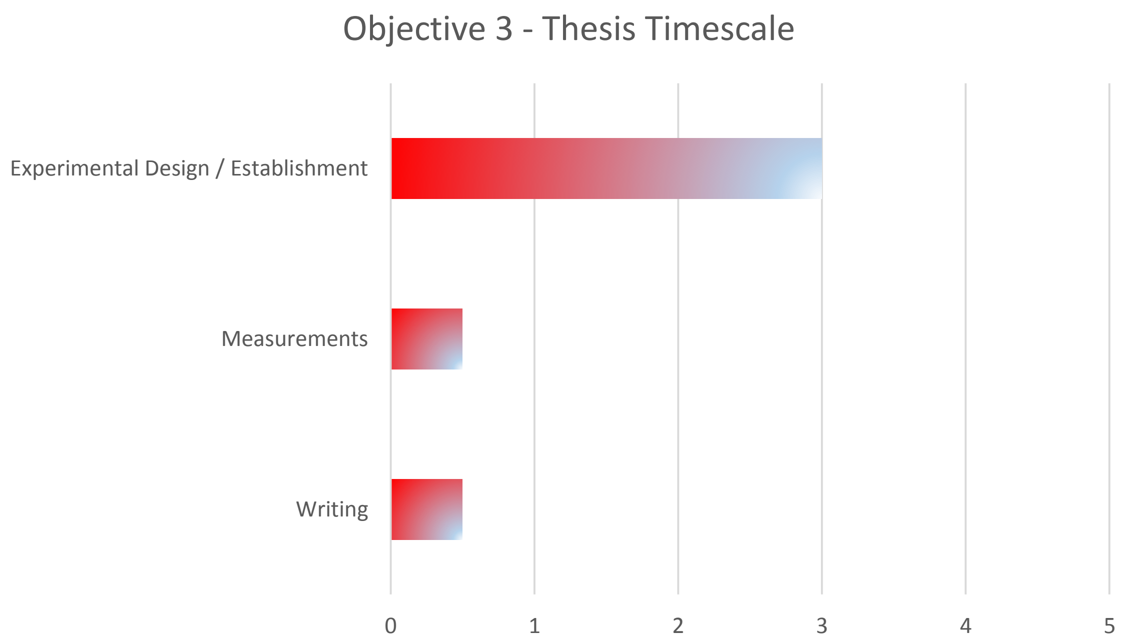
Objective 3 – Nitrogen assimilation of perennial lupin and lucerne

Goals

- Compare the ability of lupin and lucerne to assimilate nitrate from the soil.
- Assess the ability of each species to 'switch off' nitrogen fixation in the presence of high soil nitrate.
- Identify mechanisms of nitrate assimilation for each species.

Completion of goals to date

A glasshouse experiment was established on 11th April 2014 in the Alluminex glasshouse. The experiment was a randomised complete block design with six rates of nitrogen and two legume species replicated six times giving 72 pots in total. All treatments were sown into four litre pots containing a non-nitrogenous potting mix. One treatment of N (100 kg N/ha) was replicated on a high country soil, adding an additional 12 pots to the original design. Inoculants were applied to each pot at establishment, with lucerne and lupin pots receiving a 5 ml solution of Group Al and Group G commercial inoculants, respectively. Plants were defoliated and thinned on 28th May. Labelled $^{15}KNO_3$ fertiliser was applied to pots on 30th May. The plants are currently in their first regrowth cycle since N application, and are awaiting measurements.



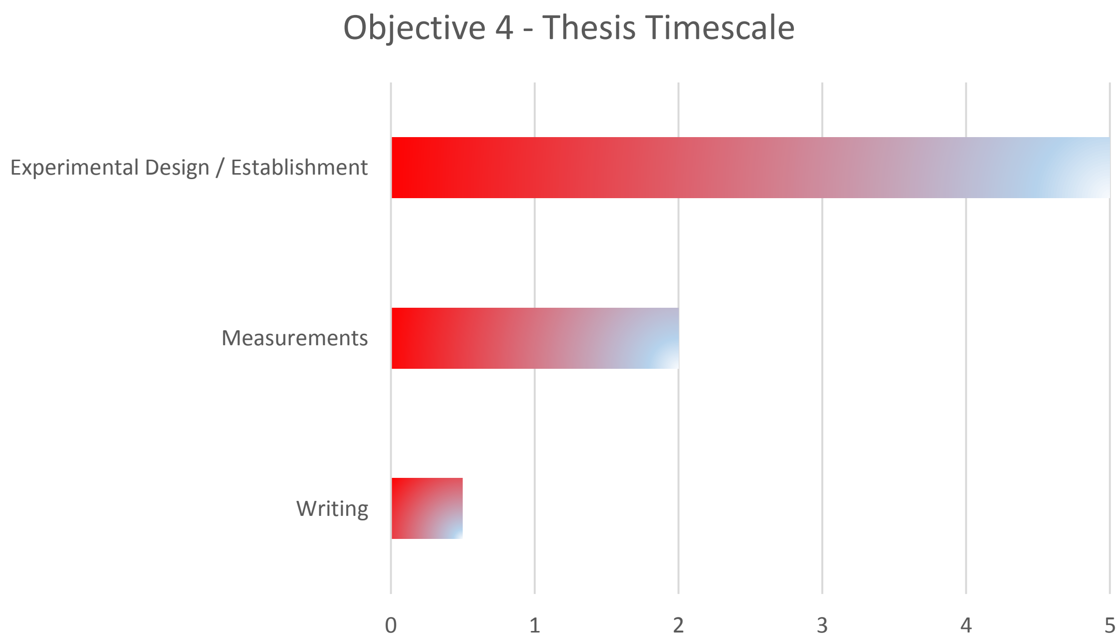
Objective 4 – Animal performance on grazed lupin/cocksfoot pastures compared with lucerne at Lincoln

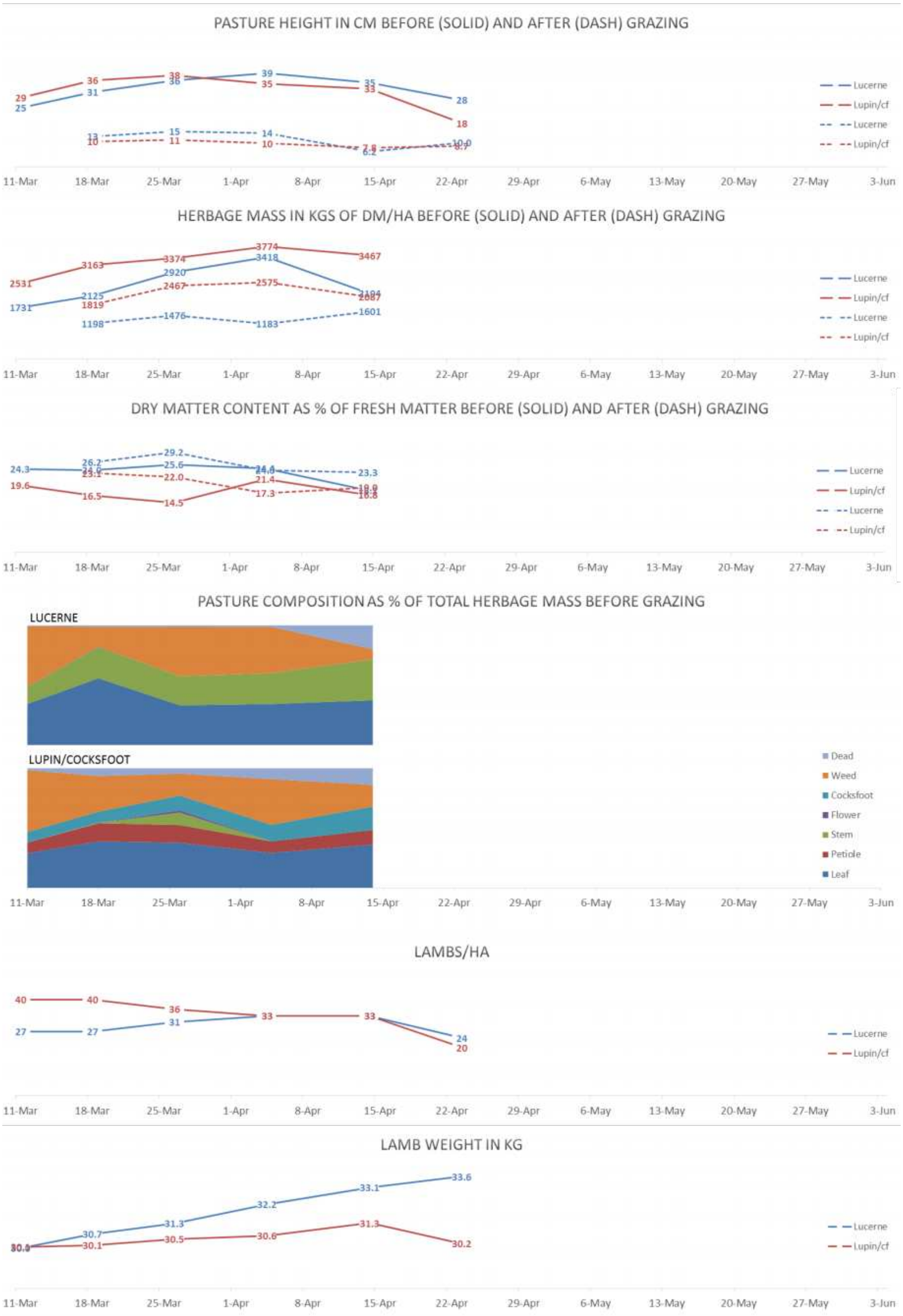
Goals

- Accurately compare the productivity and feed value of lupin/cocksfoot and lucerne pastures.
- Define and compare animal performance (liveweight gain) on each pasture.

Completion of goals to date

Three pairs of adjacent plots, each 0.25 ha, were laid out in a field at Lincoln University. One plot of each pair was selected at random to receive the lucerne and the other for the mix of Russell lupin and cocksfoot. The plots were planted on 5 December 2013. The Russell lupin was planted at 30 kg/ha with 10 kg/ha of Kara cocksfoot. The lucerne cultivar was Force 4 at 15 kg/ha. All plots were irrigated over summer and then divided evenly into five paddocks. Merino lambs were sourced from Sawdon Station and were rotationally grazing each plot from 11 March to xx date. The plots are currently in a wintered state, and all animals have been removed until plant growth is sufficient to resume grazing.





Note: the lucerne ‘leaf’ fraction includes petioles whereas lupin leaves and petioles were separated.

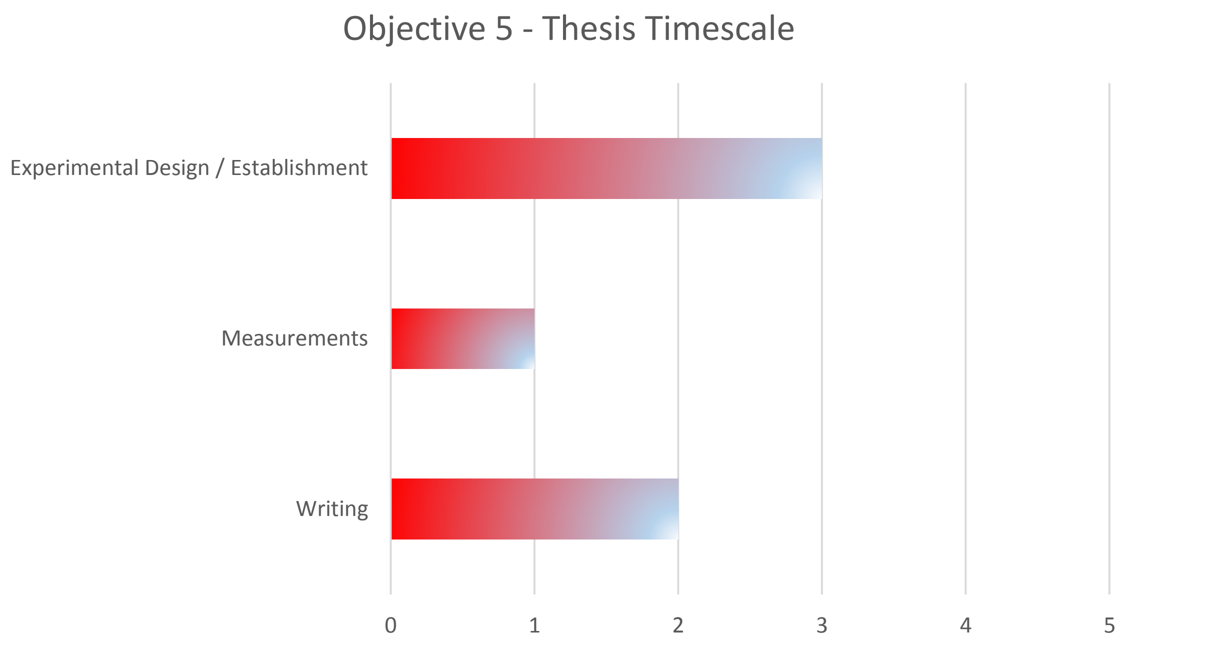
Objective 5 – Effect of subsurface lime application on the growth of legumes in acidic soils.

Goals

- Design and construct a specialised implement for the delivery of lime to subsoil layers.
- Apply lime to subsurface layers at high country sites and assess its effectiveness using legumes as a biological indicator.

Completion of goals to date.

A specialised implement was designed and constructed in conjunction with Flexiseeder Ltd. The implement was commissioned at Omarama Station on 27th February 2014. Lime was applied at five treatment levels (0, 0.5, 1, 2 and 4 t/ha) to plots measuring 20 x 20 meters. Initial applications at Omarama Station were not carried in accordance to an experimental design. However, future lime applications will be applied in a designed layout. A new experiment is due to be established in paddock H2 (pH – 5.5, Al^{3+} - 3 meq/100g) at Ashley Dene. Treatments will include four rates of subsoil lime (0, 0.5, 1, 2 t/ha) and a deep-rip treatment at 0 t/ha; to remove confounding effects of ripping (soil disturbance/aeration).



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Appendix 2 – Papers to be presented at NZGA Conference

2.1 Perennial lupin establishment and yield when sown at five different rates at Glenmore Station, Lake Tekapo.

D.J. Moot & K.M. Pollock
Faculty of Agriculture and Life Sciences, PO Box 85804, Lincoln University, Lincoln 7647, Christchurch, New Zealand
Derrick.Moot@lincoln.ac.nz

Abstract

The potential for perennial lupins to underpin grass/legume pastures is the subject of a current research programme for merino farmers in areas where more conventional legumes struggle to thrive. A previously uncultivated pasture on an acidic soil, (pH 5.0; Al = 5 mg/kg), and dominated by browntop, sweet vernal and Kentucky bluegrass was herbicided, burnt and top-dressed with 3 t/ha lime on half the area in the autumn prior to direct drilling on 12 Dec 2012. Blue and Russell lupin (*Lupinus polyphyllus*) were sown at 2, 4, 8, 12, 16 and 32 kg/ha and cocksfoot at 2 kg/ha. Yield at 4 months after sowing had increased with the lupin sowing rate; up to 5.5 t DM/ha at 32 kg seed/ha. The annual yield for the following growth season was greater than 10 t DM/ha with little response above 8 kg lupin seed/ha. There was a small but inconsistent response to the lime by the Russell lupin. Overall, lupin contributed 79% of annual yield and >90% of the spring yield at sowing rates >8 kg/ha. The sown cocksfoot and resident grasses showed a positive lime response at the lower lupin sowing rates.

Introduction

NZMerino Ltd has a Primary Growth Partnership from the New Zealand Government. One fibre of this programme aims to increase the on-farm production of merino wool from high country farms. To achieve this, the Lincoln University dryland pastures group were engaged to jointly develop a research programme. The emphasis was to identify pasture legumes that could be used as the basis for increased merino wool production. The expansion of the area of lucerne planted was identified as an obvious option for more wool production. As a consequence, rotational grazing of merino ewes and lambs on lucerne was successfully introduced and demonstrated at Bog Roy Station (Anderson *et al*. 2014). The animal performance figures have shown the benefits of higher lambing percentages and survival and greater herbage growth off the flat land, which has improved the adjacent hill country production. As a consequence, the expansion of lucerne planting is ongoing (Stevens *et al*.

2012) as farmers recognise the benefits of direct feeding in addition to its traditional role as a conserved feed for managing their 90-120 day winter.

However, lucerne is unsuitable for many regions of the high country where low pH and high (> 3.0 mg/kg) available aluminium in soils severely restrict its root growth and nodulation. Overcoming this with lime and fertilizer is possible (Kearney *et al*. 2010) but can be uneconomic or difficult where aluminium is present throughout the soil profile (Moir and Moot 2014). Therefore, additional perennial legume species are required to provide the benefits of increased forage quality, nitrogen fixation and higher yields than the resident pastures. A long term grazing trial at Mt John, Tekapo, and observations from local roadsides indicate perennial lupins (*Lupinus polyphyllus*) survive the climate and have provided an ongoing source of feed over 30 years. Despite its success in trial plots (Scott 2008) there has been little commercial sowing of perennial lupins in the high country. Therefore a research programme was developed to examine the potential of perennial lupins as a viable forage for the high country. The animal performance of merino sheep grazing lupins was quantified on-farm (Black *et al*. 2014) using the only commercially grown block of lupins in the district. At the same time, their ability to colonise a wide range of environments was confirmed along with their successful symbiosis with resident rhizobia populations (Ryan-Salter *et al*. 2014).

To complement these investigations, a more intensive agronomic research programme was established at Glenmore Station, Lake Tekapo. The site is typical of many within the region that are dominated by browntop (*Agrostis capillaris*) or sweet vernal (*Anthoxanthum odoratum*) and produce a minimal amount of quality spring herbage for grazing. The site also contained Kentucky bluegrass (*Poa pratensis*), a tough, sod-forming grass, but of little agronomic value in NZ high country. The aim was to generate guidelines for lupin agronomy including sowing rate and early grazing management. The recommended preparation in this environment is to utilize cereal greenfeeds, such as ryecorn (*Secale cereale*), for 2-3 years to assist in the breakdown of the browntop thatch (Anderson et al. 2014). This is followed by permanent pasture, lupins or lucerne. However, in this research we aimed to determine whether a perennial pasture based around lupins could be established straight out of the resident vegetation, following guidelines from Kearney *et al*. (2010). The second aim was to determine what rate of lupin seed was required to achieve this.

Materials and Methods

Site and preparation

The experiment was established at Glenmore Station, Lake Tekapo, (43.9028°S 170.4716°E; 725 m.a.s.l.). A 20 x 90 m block of resident pasture was sprayed with Glyphosate-360 herbicide (10 l/ha) in March, 2012, then the residual burnt in April. Lime at 3 t/ha was applied on 17^{th} May to half of the area (10 x 90 m). The area was then fallowed through winter and spring before a further Glyphosate application of 4 l/ha was applied on 4 Dec 2012. A week later, the experiment was drilled using a 'Flexiseeder' precision plot drill fitted with tine coulters. Fertilizer (100 kg Cropmaster 20; NPKS, 19.3 10 0 12.5) was applied simultaneously via the drill's coulters from a separate fertilizer box. No additional fertilizer has been applied to ensure a low cost approach to development, on this land with a pH=5.0 and excahangeable aluminium at 5.0 mg/kg (Moir and Moot 2014).

Experimental design

The area was divided across its 90 m axis into three 20 x 30 m blocks (replications). The ± lime treatment formed the main plots. Each block was divided into six subplots of 4.2 x 20 m, which traverse the full 20 m width of the ±lime treatment. Within these, lupin was sown (LSR) at 2, 4, 8, 12, 16 or 32 kg/ha along with 2 kg/ha of 'Vision' cocksfoot (*Dactylis glomerata*). Each subplot was also split along its length to form 2.1 x 20 m (one drill width) sub-subplots for either 'blue' or 'Russell' lupins. A split-split-plot analysis of variance consisting of blocks (3), main-plots (± lime), subplots (LSR = 6) and sub-subplot (variety = 2) was used to assess the statistical significance of the applied treatments. The design was fully randomized at the sub-plot and sub-subplot levels but not at the main plot (lime) level.

Measurements

Germination (%) of the unscarified lupin seed at 7 days was 65% for blue lupin and 55% for Russell lupin but seeding rates were not adjusted for this. Seed was from Rosevear & Co. Ltd, Ashburton, from a local commercial grower. Germination, originally tested in September 2011 by Seedlab (no. 112365 & 112366) was 80% at 30 days for blue lupin and 67% for Russell lupin.

Field measurements on six dates included: 1) plant emergence at six weeks after sowing (24 Jan 2013); 2) lupin establishment as determined by plants with 3 or more fully expanded leaves, dry matter (DM) yield using a capacitance probe and visual sward composition on 7 March, 2013; 3) machine harvest for DM yield and botanical composition on 17 April, 2013; 4) capacitance probe measurement for relative yield at 24 October, 2013; 5) machine harvest for total spring DM yield and sward composition on 2 December 2013 followed by grazing and DM assessment of the residual; and 6) hand harvest for DM yield composition and plant population on 24 March 2014 to assess the summer recovery after grazing and complete the estimate of annual DM yield. In addition, 32 plants were randomly selected and individually marked across the experimental area in April 2013 and then scored to assess survival in September 2013.

Plots were grazed as part of the total 2 ha paddock on three occasions after sowing. The first was with 700 ewes for 2 days in mid-June after the plants had grown for the full summer, many had flowered and vegetation was dying back in the early winter. The second was with 1200 merino 2-tooths for 4 days following the yield assessment on the 3 December 2013. The third occurred after the final yield determination for the 2013/14 season on 24 March, 2014.

Temperature and rainfall were recorded on site and compared with NIWA long term records (Fig. 1). Temperatures were near normal. An 80 mm rain event at the beginning of January 2013, four weeks after sowing, was ideal for emergence and establishment. This rain and the conserved moisture from the spring fallow allowed consistent growth through to autumn. Heavy June rainfall in addition to the remaining winter rain meant soils started spring at field capacity. Rainfall during spring of the second year was slightly higher than normal but the summer and early autumn were drier which restricted pasture growth after the hard December grazing.

Results

Plant population

The lupin emergence, January 2013 and establishment, March 2013 (Year 1) were affected by sowing rate (P<0.001; Fig. 2a). Over 40 seedlings per m^2 emerged in January at the highest sowing rate, and plant numbers were comparatively stable over the next two months. There were at least 12 plants per m^2 in plots with a sowing rate ≥8 kg/ha and a difference between lupin varieties ($P=0.002$) at the end of the establishment period in March 2013 (Fig. 2b). However, by March 2014 (Year 2) lupin plant numbers had dropped to below 12 plants/m^2 across all sowing rates (Fig. 2c) and below 9 plants/m^2 at sowing rates <12 kg/ha. Of the 32 marked plants from the previous autumn, none had died or appeared weakened as a result of the autumn grazing or winter frosts when viewed in September, 2013 (Year 2).

The mean cocksfoot population in March 2014 was only 3.6 plants/m^2 but plants were vigorous. Despite a lupin sowing rate effect ($P=0.013$) on the cocksfoot population, there was no apparent trend over the six sowing rates. However, the mean cocksfoot population was 4.3 and 2.8 plants/m^2 ($P<0.001$) with 3T and no lime, respectively, and 3.1 and 4.0 plants/m^2 ($P=0.024$) when sown with blue and Russell lupins, respectively.

Year 1, Yield from sowing to first harvest

The capacitance probe measurements on 7 March 2013 and visual estimates of plant cover showed the same pattern as the mechanical harvest on 18 April 2013. Yield increased with the lupin sowing rate to over 5 t DM/ha at 32 kg seed/ha (Fig. 3a; $P<0.001$). There was a dominance of lupin herbage in all treatments with <5% cocksfoot and other components. Sowing rates between 8 and 16 kg/ha produced >2 t DM/ha. Blue lupin yielded slightly more than Russell lupin (Fig. 3b; $P=0.027$), possibly reflecting the 10% higher germination and emergence. Bare ground decreased from 64 to 7% with the increase in sowing rates ($P<0.001$). It decreased from 43 to 27% overall with liming ($P=0.019$). There was 37% bare ground with Russell lupin and 33% with blue lupin ($P=0.008$). Re-established resident species were more prevalent at the lower sowing rates.

Year 2, Annual yield (Dec 2013 and March 2014)

The mean annual DM yield across all treatments for Year 2 (sum of harvests on 3 Dec 2013 and 24 March 2014) was 11.0 t/ha (Fig. 4a) but differed with sowing rate. Lupins sown at 2 kg/ha produced 6 - 8 t DM/ha compared with 11-15 t DM/ha at 8 kg/ha or higher for all but the unlimed Russell lupin pasture ($P<0.022$ for the LSR x lupin variety interaction). Overall, the lupin component was 80% of the annual yield (Fig. 4b) and cocksfoot 16% (Fig. 4c). The lupin yield (Fig. 4b) increased to 8 kg/ha with blue lupin being more responsive than Russell lupin. The proportion of cocksfoot (Fig. 4c) was greater when sown with Russell than blue lupin ($P<0.001$).

Over 80% of the total Year 2 yield was from the December 2013 harvest which averaged 9.1 t DM/ha. The blue lupin contributed more than 90% of the December yield at sowing rates greater than 4 kg/ha while cocksfoot contributed 10-20% at the lowest sowing rate but less than 10% at sowing rates above 8 kg/ha. There was little bare ground at this stage. Regenerating resident species, mostly Kentucky bluegrass, browntop and sweet vernal, invaded the lower sowing rate plots. Lodging, defined as more than 20% of lupin plants toppled was prevalent in blue lupin at sowing rates ≥16 kg/ha but not for Russell lupin. This occurred in response to gale force wind gusts (60 - 98 km/h) from the NNE coupled with light rain during the weekend prior to the spring harvest (NIWA Cliflo data from Lake Tekapo EWS). The flower stalks had just reached their full height and were likely to be at their most susceptible stage for lodging.

For the March 2014 harvest, the mean cocksfoot yield (1.0 t DM/ha) accounted for 53% of the total harvest and lupin contributed 42%. The only treatment effect at this harvest was that blue lupin yielded 0.973 kg DM/ha and Russell 0.635 kg DM/ha ($P<0.001$). There was up to 60% bare ground at the lowest sowing rate and 40% at the highest ($P<0.001$). The mean bare ground was 49% for blue lupin and 55% for Russell lupin ($P=0.021$).

Grazing and utilization of the spring growth.

Following the 3 December 2013 yield harvest, the sheep initially ate the clover from surrounding experiments and then moved into the lupin experiment. Here they consumed the flowers and green leaf first. After two days there was little green leaf left on the lupin, only flower stalks and a few leaf petioles remained. The mean utilization of the lupin-cocksfoot pasture was 64% for 3T lime and 52% for no lime ($P<0.002$). Utilization of the lupin alone was 71% and 49% for the 3T and no lime, respectively ($P<0.001$). Separation of the lupin plant parts from 20 of the pre-grazed samples showed 45% of the lupin DM was from the flowers, leaf lamina and pods and 49% from the flower stalks and leaf petioles.

Discussion

Successful establishment of perennial lupin based pastures was achieved through the ‘double spray’ technique with glyphosate in autumn, followed by a burn, and then the second glyphosate spray immediately pre-planting the following spring. This method of preparation effectively reduced the competition from the thatch of browntop and Kentucky bluegrass that dominated the site. Importantly for the success of the 'double spray', autumn rainfall (Fig. 1) ensured the grasses had sufficient green leaf to take up the chemical. This is then translocated to stolons and rhizomes to increase the effectiveness of control. The resultant dead material was able to be burnt and removed before the second, spring application killed the regenerating grasses and other weeds. A similar approach was advocated by Kearney *et al.* (2010) to successfully establish lucerne in Central Otago out of resident vegetation. In both examples minimal seedbed preparation was used to shorten the process of establishment. However, caution should be exercised when advocating this establishment approach. In a dry autumn, the herbicide application may be ineffective and the resident vegetation reinvade more quickly. In these low productivity environments, where pasture establishment is a comparatively expensive exercise, the more traditional approach of 2-3 years of cereal greenfeed carries less risk (Anderson *et al*. 2014). The cereal greenfeed has the added advantage of providing winter feed while heavy mob stocking assists the mechanical breakdown of the browntop thatch. It also remains to be seen how long these newly established pastures remain free of reinvading weed species and this will be monitored for the next two years.

It was apparent by the end of the experiment that the different sowing rates of perennial lupins had affected the botanical composition of the pastures established. For both blue and Russell lupins a sowing rate of 8 kg/ha is recommended. At this rate there was an adequate population of plants established, and these survived to the first autumn grazing and into year two. We must emphasize that there was favourable rainfall for the establishment phase which allowed this grazing. In a more normal, drier, summer (Fig. 1) the lupins may need a laxer grazing management at establishment. A key component of the current success was the fallow in spring to conserve moisture which ensured emergence. Without the follow-up summer rain growth in this establishment season would be reduced. The highest sowing rates used here were insurance in case we experienced a dry summer year. The lower sowing rates left more bare ground available for cocksfoot establishment but also added the threat of less desirable resident grasses and broad leaf weeds. The yield from all sowing rates showed the potential for lupins to increase the amount of herbage grown. The Year 1 yield of ~3 t ha^{-1} from sowing to grazing in autumn consisted of vegetative plants that produced a cluster of long-petioled leaves from a developing crown. Some plants had flowered by the end of the first summer. It is likely that the partitioning of growth of lupins follows that of other perennial legumes, such as lucerne, where the emphasis is on below ground establishment in the first year (Thomas 2003). Russell lupin seedlings from a nearby experiment sown at the same time as the present experiment and dug up in May 2013 had mean root, crown and shoot DM of 37.0, 7.32 and 41.7 g, respectively (Moot 2013). This first summer allowed sufficient growth to occur for plants to cope with a light grazing in autumn, survive the winter die back and regrow at similar numbers in spring. The yield in Year 2 was over 10 t DM/ha for crops sown with 8 kg/ha or more and this was predominantly produced by lupin in spring (Fig. 4). The timing of this feed has been shown to suit ewes with lambs in this environment (Black *et al*. 2014). The height of the lupin plants provides additional ecological service of shelter and ground cover. The highest lupin sowing rates also showed weed suppression but plants were relatively spindly and weakened from the intense competition.

The use of cocksfoot as a companion species was successful when included at 2 kg/ha. The cocksfoot benefitted from the addition of 3 t/ha of lime more than the lupins and made up around 20% of the yield in both years at the lupin sowing rate of 8 kg/ha or less. The aim of the cocksfoot as a companion species is to provide ground cover amongst the distinct lupin plants. The grass is then able to grow with the nitrogen provided by the lupin grazing and offers feed at times when the lupin may be less palatable (Black *et al.* 2014). The utilization of lupin feed was enhanced by the addition of lime. However, the lupin growth was not enhanced by the lime which suggests the use of lime would be advantageous to the quantity and quality of companion species and maximize the feed on offer. Lupins are known to be unpalatable to stock because of leaf alkaloids. While not the first choice for the sheep during the December grazing, once started, the sheep quickly devoured the flowers and leaves which are the most nutritious feed (Black *et al*. 2014). Earlier grazing of the lupin stand may allow the companion species such as cocksfoot to be grazed preferentially to the lupins before the latter's palatability increases with flowering. The earlier and more frequent grazing of the cocksfoot also reduces its unpalatable reproductive stem growth and promotes a more uniform sward as opposed to clumping.

The significant drop in plant numbers of lupins by March 2014 may represent self-thinning but also the consequence of the hard grazing in December. The plants that remained had become dominant and a population of more than ~10 plants/m^2 would seem unnecessary to maximize lupin yield by this point. It remains to be seen whether the population will persist but results from previous work (Scott 2008) suggest longevity. Should the population be diminished by the grazing it may be possible to thicken up a stand by allowing some of the flowers to develop pods and drop seeds. How successful this is in this environment, where a resident seed bank of weeds is apparent, remains to be measured. The persistence of blue versus Russell lupins also remains to be seen. The 10% higher germination rate for blue lupin appears to have given an initial advantage at sowing and establishment (Fig. 2). This may have benefitted its yield in Year 2 (Fig. 4b) but both varieties appear to have established a sufficient plant population to maintain production into Year 3. The vigorous growth of this species in the presence of high aluminium (Moir and Moot, 2014) in the soil highlights its potential to provide a nitrogen fixing perennial legume in an environment that is unsuitable for lucerne.

Conclusions

Perennial lupins were successfully established into the resident vegetation at Glenmore Station. These first two years results show a thriving stand with an expanding cocksfoot population that will significantly out-yield the resident browntop dominated pasture. A sowing rate of about 8 kg/ha was adequate for plant establishment of both Russell and blue lupins, and the application of lime aided the cocksfoot growth. In these highly acidic soils, that have aluminium levels that are toxic to lucerne, the lupins have provided a viable perennial legume option.

Sow lupins at 8 kg/ha, or lower if germination is >80%. Use higher rates where canopy dominance is necessary to control re-invasion by resident species. Use lower rates where moisture is reliable, weed control and seed bed preparation are maximized and when desirable companion species are sown with the lupin. Use lime to benefit the companion species and improve pasture quality for stock.

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NZMerino Ltd and Ministry of Primary Industries provided funding. We thank Will and Emily Murray of Glenmore station for assistance with accommodation, fencing, land preparation, machine work, on-trial sheep grazing, and on-site records. Denis Fastier, Simons Hill Station provided support and on-going field co-ordination. Anna Mills and Simon Hodge, Lincoln University, provided assistance with statistical analysis. Lincoln University students and technical staff provided assistance in the field and laboratory.

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List of Figures

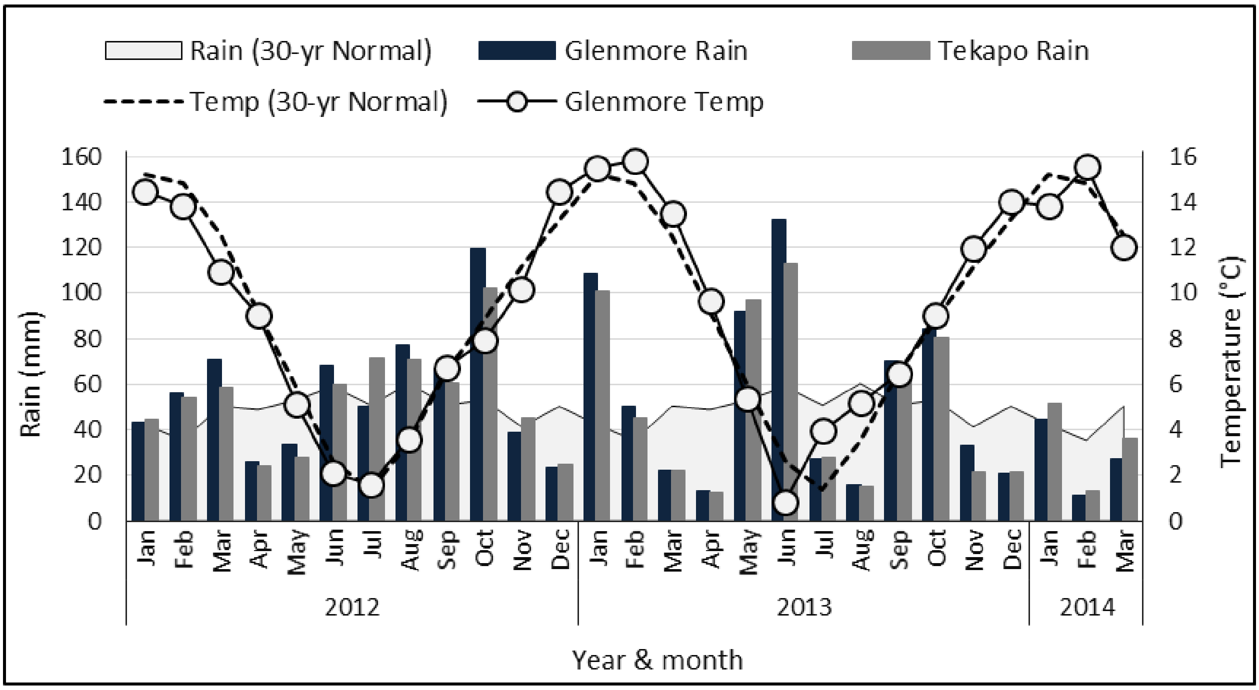

Figure 1. Rainfall and air temperature recorded on site at Glenmore. Current rainfall and 30-yr normal rain and mean temperatures from Lake Tekapo EWS climate station (NIWA CliFLo data 2014) are included.

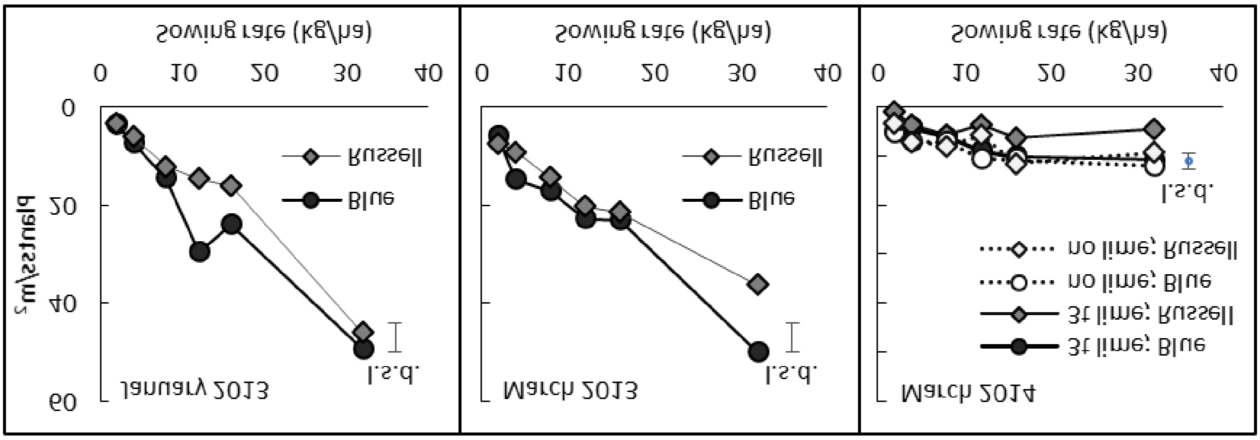

Figure 2. Plant population of perennial lupin sown at 6 rates on 11 December, 2012, during the establishment phase in, January and March, 2013 (Year 1), and at 24 March 2014 (Year 2), in response to ±lime, lupin sowing rate and lupin variety at Glenmore Station. There was a lupin x sowing rate interaction in Year 1 (P<0.01) and both lime x lupin and sowing rate x lupin interactions in Year 2. Least significant differences between means (l.s.d.) are shown.

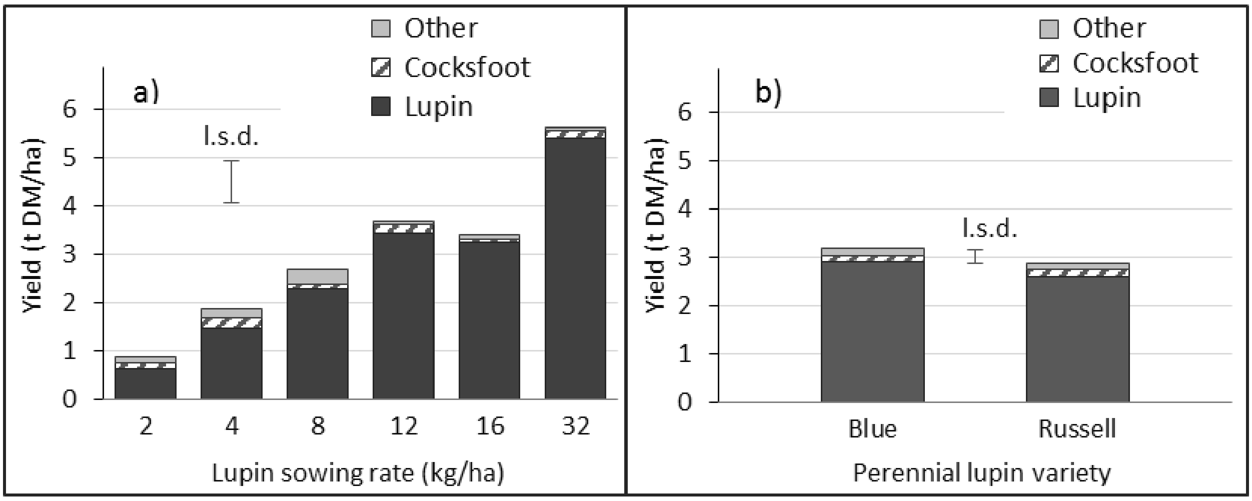

Figure 3. Total dry matter (DM) yield of lupin/cocksfoot pasture on 18 April 2013 from sowing on 11 December,2012 in response to a) sowing rate and b) lupin variety. Least significant differences between means (l.s.d.) are shown.

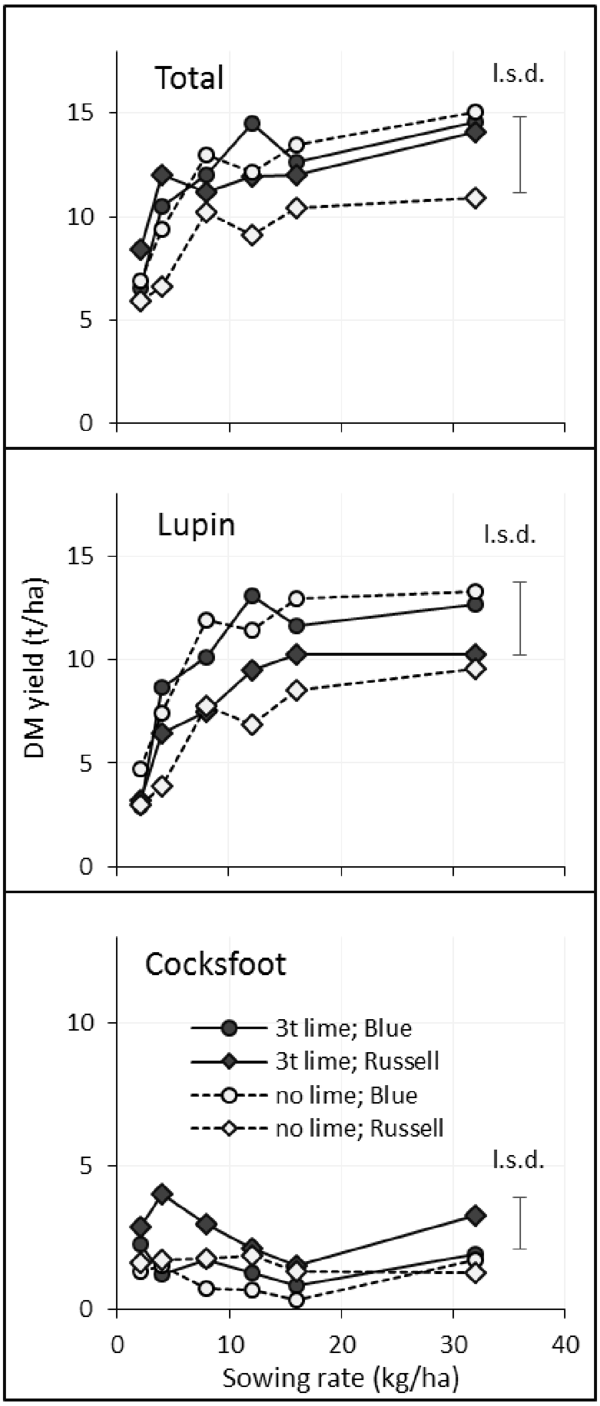

Figure 4. Mean annual DM yield in Year 2 for pastures at Glenmore Station sown with six rates of each of Blue and Russell lupin. Least significant differences (l.s.d.) are shown.

2.2 Integrating lucerne (*Medicago sativa* L.) into a high country merino system

D. Anderson[1], L. Anderson[1], D.J. Moot[2] and G.I. Ogle[3]

[1] *Boy Roy, Private Bag 3, Kurow*

[2]*Faculty of Agriculture and Life Sciences, PO Box 85084, Lincoln University 7647, Canterbury*

[3]*graeme.ogle@rezare.co.nz*

Abstract

Farm systems in the dry sub humid region of the Upper Waitaki predominantly graze merino ewes on extensive oversown and topdressed hill country. Small areas of improved pasture are used to conserve supplementary feed and grow winter crops. The slow growth rate of merino lambs means they are traditionally retained on these improved pastures to finish in the following spring. In this system livestock demand peaks in our driest month of January and continues to be high through winter. Bog Roy is a farm that has changed this system and now established 200 ha of lucerne with the goal of fully feeding ewes during lactation. Pre-natal lamb growth rate has increased from 205 to 235 grams/head/day opening the opportunity to sell heavier lambs in early January. Ewe lamb replacements are reaching heavier pre-winter live weights (38 kg versus 35 kg) and the flow effect is higher two tooth scanning percentages (129% versus 111%) and weaning percentage (100% versus 84%). Lucerne has also improved the feeding of mixed age ewes from lambing to weaning and lamb mortality has reduced from 30% to 21% increasing weaning percentage from 115 to 130%. The store production system also means livestock demand is kept low during the dry period and remains low through winter. Conserved feed is now only required for 50 days compared with 100 days in the traditional system. This has reduced supplementary feed costs from $10.33/SU to $4.82/SU. Shifting ewes to rotationally graze lucerne in large mobs early in the growing season has decreased the stocking rate on hill country. This has allowed cover to build during each spring with promising responses from legume species.

1 INTRODUCTION

2 FARM DESCRIPTION

3 CONTOUR, SOILS AND VEGETATION

Bog Roy is a 2860 ha station situated on the south eastern shore of Lake Benmore in the Upper Waitaki catchment of the South Island high country. The property starts at 400 m above sea level and rises to 1000 m above sea level. It has a dry sub humid climate with 380-400 mm of annual rainfall. Typical of high country stations, a large proportion is extensively farmed. Unimproved short tussock grassland running 0.3 SU/ha makes up 47% of the area while oversown and topdressed hill country running 1.5 to 2.0 SU/ha a further 42%. The remaining 11% is made up of 200 ha of lucerne and 130 ha of mainly flood irrigation.

Soils are derived from loess deposited over thousands of years from the prevailing westerly wind. Flat land varies from shallow stony fluvio-glacial deposits through to deep loess. The low rainfall results in Pallic soils that are naturally high in pH and phosphorus but low in organic matter and sulphur. Pasture growth follows the pattern of altitude, aspect and soil depth. In spring growth starts in mid-August on mid-altitude sunny hill country making it favourable for lambing ewes on the 20th of September. Growth is normally reliable until mid-November when sunny aspects and shallower soils start drying off. Shady aspects and deeper soils continue a further 3-4 weeks. By late December evapotranspiration rates are higher than rainfall and growth is expected to cease for at least 4 – 6 weeks. Evapotranspiration rates are lower in March and April so autumn is important for growth which then ceases from early May through to mid-August due to cold temperatures.

4 STOCK

The property runs an 18.0 micron merino flock with 3900 breeding ewes and 1700 ewe hoggets. Lambs are weaned in mid-January and all wether lambs are sold store. Ewe hoggets are kept through winter and 1000 are selected for replacements in mid-July. After shearing in mid-August 500 of the cull ewe lambs are sold as replacement stock and 200 are sold to the works. A beef herd of 110 cows and 20 in-calf heifers sells all calves at weaning with replacement heifers purchased in.

5 THE MOTIVATION TO CHANGE OUR SYSTEM

We took over ownership of Bog Roy in 2006. With the debt incurred we were intensely focussed on cashflow and profitability. Benchmarked against other merino properties the business performed above average. This implied growing the business would not be straight forward. Also of concern was the decline in the condition of the oversown and topdressed hill country. *Hieracium pilosella* was increasing and clover, once abundant was declining. Historically the oversown and topdressed hill was the platform for the lactating ewe from lambing to weaning.

At this time the renewal of a water consent for flood irrigation required conversion to spray irrigation and considerable capital expenditure. Initially this seemed an opportunity to grow the business by increasing the area irrigated and reduce our reliance on a variable summer. However, a detailed financial analysis showed the development might only generate sufficient added income to service the new borrowings. Beyond this, the only benefit was a gain in the capital value. To realise this value would require an exit strategy. The desire to continue rather than exit farming lead to additional options being considered. This meant investigating whether per head performance of the animals could be improved and feed demand better matched to feed supply.

The merino breed is characterised by a low lamb growth rate. This starts *in vitro* with low lamb birth weight, a cause of high lamb mortality and low pre-natal growth leading to low weaning weights and finishing performance. Merino lambs are therefore not favoured by lamb finishers and are heavily discounted in dry years when lamb finishers prioritise heavy lambs that can be finished quickly. In contrast the early spring market for lambs carried through winter is comparatively stable (Ogle 2009). Merino systems have adapted to this climate and market volatility by retaining the highest proportion of lambs possible within their feed supply to sell from October to December in the following year.

We experienced a very dry season in 2010 that reinforced that the business is dominated by the summer dry and a long winter. In spring our most productive stock class, lactating ewes were set stocked on hill country which was declining in productivity and forage quality. Finishing hoggets grazed the most productive land followed by a short period where this high quality feed was conserved to carry the current lamb crop through the next winter. Ewes came off hill country in acceptable condition but leaving very low covers. This system was chasing every blade of grass either to finish last year's lamb crop or conserve it for winter. The hill country supporting the lactating ewe seemed unsustainable and highly variable from one year to the next.

6 Analysing the system

We started by focussing on what we could do to align our feed supply and demand. A model of our farm using the Farmax computer program (Marshall *et al.,* 1991) demonstrated the misalignment with demand and supply (Figure 1). Pasture growth peaked in November while livestock demand peaked in January; our driest month. For six months of the year feed demand was higher than feed supply. Shifting feed into these months made for an expensive farm system.

The obvious opportunity for changing feed supply was irrigation. Realising irrigation development required an exit strategy so dryland plants were considered. The opportunity came from reading an article about Doug Avery (Avery *et al.*, 2008) who had re-designed his drought prone property using lucerne (*Medicago sativa*). This reinforced the simple point that lucerne was the most efficient pasture plant in converting spring soil moisture into pasture dry matter (Moot *et al.,* 2008). It followed that in our 380-400 mm rainfall environment, where summer moisture is limiting, we should be maximising the use of this species.

Another pivotal experience was a study tour to South Africa where farmers were observed achieving 140% lambing from merinos, which contrasted with the New Zealand experience of 80 – 100%. Their systems emphasised the need to fully feed ewes throughout the year and prioritise light ewes from weaning to tupping. We started to consider how lucerne combined with a high ewe reproductive performance could help re-design our system. We identified four key strategies to change;

- Maximise production of high quality feed for lactation. This involved replacing all grass pastures, including irrigation, with lucerne.
- Increase feed demand during the height of the growing season. This involves fully feeding ewes from the start of lambing throughout lactation on the highest quality feed. Well-fed ewes in good condition are less likely to mismother and this would decrease lamb mortality. Resulting increases in lamb growth rate would achieve a higher lamb weaning weight.

- Reduce feed demand in the driest month. This involves selling surplus lambs store in January. With a heavier lamb at weaning the store price would not be as heavily discounted.
- Reduce demand during winter. Weaning heavier ewes reduced the need to put condition back on for tupping. This feed would be available for priority feeding of ewe hoggets to achieve a higher liveweight before the first winter. The gain would follow through to their first mating.

We set targets, which if achieved, would generate greater profit by increasing farm revenue and decreasing the cost of winter feeding (Table 1). The productivity of lucerne in this environment was not clearly understood but a yield of 5.5 tonnes of dry matter annually was assumed.

7 MAKING THE TRANSITION

We started the process by seeking assistance from Professor Moot. After the third year of making changes the New Zealand Merino Company came on board and provided funding to expand the work that Lincoln University had initiated. This involved cutting pasture cages of lucerne on a monthly basis to generate data to compare the production from unimproved and improved pastures and to compare dry land lucerne with irrigated pastures and lucerne grass mixes. The cut samples were sent to Lincoln University for oven drying and data analysis. At the same time the pre and post grazing height of each lucerne paddock were recorded when stock were moved into and out of a paddock. At the end of the season these data were also sent to Lincoln University to analyse the amount of herbage produced and consumed from each paddock.

The initial transition started in a modular fashion with a block chosen that could be subdivided into six paddocks. This provided a system where a mob could be introduced at lambing and rotationally grazed until weaning. Doug Avery's experience highlighted the value of contour planting lucerne. This meant planting lucerne in paddocks that had a mix of valley basins that could be established into lucerne while leaving steeper or unfavourable areas undeveloped. These paddocks provide necessary stock shelter and ewes can be offered both high quality lucerne and grasses that balance their diet. Thus, the deeper soils are planted in lucerne and the shallower soils left with resident vegetation to provide other ecological services.

Lucerne is established after two or more years in a fodder crop. Fodder crops provide opportunities to repeatedly spray resident vegetation and is the cheapest time to control weeds in lucerne. The number of years in fodder will depend on how well these weeds have been eliminated. Ryecorn (*Secale cereale*) is used because it does not depend on rainfall during summer. Land is sprayed off in spring while there is still available soil moisture and this is conserved for planting in January. During this summer fallow any emerging weeds are sprayed, again to conserve moisture but also to eliminate resident vegetation. Ryecorn is an important component in the lucerne system because it provides feed in the months where lucerne is dormant.

8 MANAGING THE LUCERNE SYSTEM

Lucerne is managed in the following phases. Ewes are scanned into singles and twins and foetal aged into early, mid and late lambers. Twin ewes were the priority for lucerne because, with two lambs they have the greatest revenue potential. Foetal aging gives the ability to progressively set stock each lucerne block (for about 4 weeks at 7 ewes/ha) when it is ready; a minimum of 15-20 cm in height. At the end of lambing ewes start a rotation with a maximum of 10 days in each paddock and a minimum of 30 days before returning. If the pre-graze height of a lucerne paddock gets above 45 cm it is dropped out of the rotation and either cut or grazed with another mob. Conversely, if it gets too short another paddock is added to the rotation to ensure we are not opening up the lucerne canopy to allow bad perennial weeds like couch (*Elymus repens*), yarrow (*Achillea millefolium*) and dandelion (*Taraxacum officinale*) to establish during the set stocking period.

From weaning in early January the aim is to allow lucerne 4 to 6 weeks to flower and replenish root reserves (Moot *et al*., 2003). Ewes are condition scored with those above 3 grazed on the hill while those below are grazed around the flowering lucerne. Our aim is to have all ewes at 3 condition score or better by tupping. The aim in winter is to maintain ewe condition score, particularly for twin ewes. From autumn ryecorn is fed supplying most of our winter supplements through to late autumn - early winter. After this we use silage to fill the gap until ryecorn starts growing again in early August.

9 RESULTS AND DISCUSSION

The assistance we received was critical in giving us confidence to rapidly scale up the lucerne system. The pasture dry matter measurements showed how productive lucerne was (Figure 2). The dryland lucerne, irrigated lucerne and lucerne and cocksfoot produced 8.8, 10.5 and 11.5

tonnes of dry per hectare per year (t DM/ha/yr), respectively. This compared with 6 t DM/ha/yr from native and oversown and topdressed areas (Figure 2).

As more blocks were developed the majority of twin ewes could be run on lucerne. With rotational grazing the recovery of paddocks can be seen more clearly, and the time of shift targeted for about 3.5 t DM/ha, or 40 cm height, on entry (Figure 3). This allows forward planning if recovery rates are faster or slower than expected. Fast recovery means more ewes and lambs can be introduced to the system. Equally, if spring rainfall or temperatures are below average the slower regrowth can be targeted to the mobs that most need it. This also gives an early warning if a feed deficit is developing.

Another benefit has been that our hill country becomes progressively de-stocked during October. Over the past three years de-stocking the hill during the growing seasons has seen an increase in legume content. Initially, Haresfoot Trefoil (*Trifolium arvense*) covered the hills but now there are a number of clovers including white clover (*T. repens*) and striated clover (*T. striatum*) with a noticeable reduction in *H. pilosella*. This has encouraged us to increase fencing subdivision to establish an effective rotational grazing regime. With extra spring growth over a large area a buffer is created that can be used in summer to maintain ewes at a time when we traditionally had low covers and were in danger of overgrazing the hill areas.

Table 1 shows how livestock production in the 2013/14 season compares against our historical performance and the three year goal we targeted for this new system. Ewe hoggets are exceeding the new 1st of May live weight target (38 kg versus 37 kg, respectively). This has flowed through to two tooth performance. Scanning has improved from 111% historically to 129%, and weaning has improved from 84% to 100%. This means lamb mortality has reduced from 24% historically to 22%. Mixed age ewes were already scanning well (165%) and while this has not changed lamb mortality has decreased from 30% to 21%. We attribute this reduction to ewes in improved condition and well-fed from the start of lambing. As discussed an important component in the new system is achieving lamb high growth rates during lactation so that at weaning we have heavy lambs that are favourable for the store market. Figure 3 shows the total weight of weaned lamb has increase by 18% from an 8% increase in mated ewes.

The combination of selling surplus lambs store, the ryecorn crops used for lucerne development and renewal, and the improvement in the feed wedge on our hill have reduced our feeding out period from 100 to 50 days. Supplements are no longer fed to cattle as there is normally sufficient feed left to clean up on the hill. In 2010 we spent $10.33/SU on supplementary feeding and this has reduced to $4.82/SU in 2013.

10 CONCLUSIONS

In our dry environment lucerne provides the most efficient means of converting soil moisture into forage. The quality of lucerne enables high livestock growth rates in spring and early summer. This makes it possible for us to produce heavy lambs at weaning which opens the opportunity for a store production system. We have shifted away from a system that produced light lambs that must be kept a further 10 months, four of these having negligible pasture growth. We have created a system that matches the biophysical components of our environment. This alignment has had other benefits. Feeding stock well has increased young ewe performance and reduced overall lamb losses improving reproductive efficiency. It has also reduced our dependence on dry hill country during spring and summer. This has allowed a de-stocking period conducive to clover and building cover for late autumn and early winter.
In the old system stock were spread across the hill and it was difficult to clearly understand how well ewes were being fed until the day of weaning. In contrast with the modular approach to integrating lucerne, mobs are allocated to blocks and rotationally grazed. Lucerne growth can be estimated from soil moisture and the amount of days feeding ahead of ewes can be calculated. Together these changes provide an efficient system with hill country that is improving and one that we are more able to plan and control. The increase in lucerne area has decreased the pressure on the farm and, importantly, the farmers.

11 ACKNOWLEDGEMENTS

NZMerino Ltd through their primary growth partnership for financial support of data collection and analysis by Dr Keith Pollock and the Lincoln University dryland pastures group. Denis Fastier and Graham Brown for valued support during the process of change.

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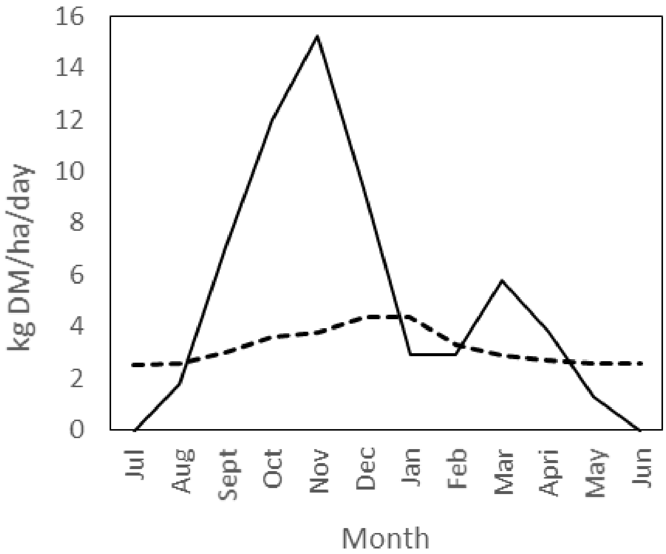

Figure 1 The feed supply (solid line) and feed demand (dashed line) calculated for Bog Roy Station using the Farmax modelling program.

Table 1 The performance of the historic system, three year targets for the new lucerne based system set in 2010/2011 and the actual performance after 3 years as measured in 2013/14 at Bog Roy station.

	Historic (Pre 2010)	Year 3 (target)	Year 3 (actual)
Young stock			
Ewe lamb weight May (kg)	35.0	37.0	38.0
Two tooth scanning (%)	111	115	129
Two tooth weaning (%)	84.0	92.0	100
Two tooth lamb mortality (%)	24.0	20.0	22.0
Mixed age ewes			
Tupping weight (kg)	57.0	60.0	59.5
Ewe scanning (%)	165	165	165
Ewe weaning (%)	115	125	130
Ewe lamb mortality (%)	30.0	25.0	21.0
Lamb weaning weight (kg)	27.0	29.0	29.0
Lamb growth rate (g/hd/day)	205	235	235

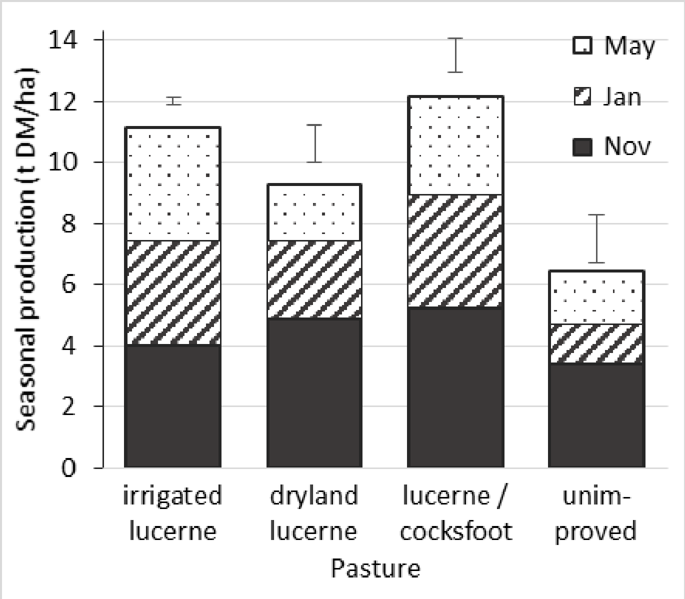

Figure 2 The annual average dry matter production measured from monthly cuts for the 2011/12, 2012/13 and 2013/14 seasons for irrigated lucerne, lucerne, lucerne and cockfoot mix and from undeveloped native. The growth season is divided into periods to end of November, January and May, respectively.

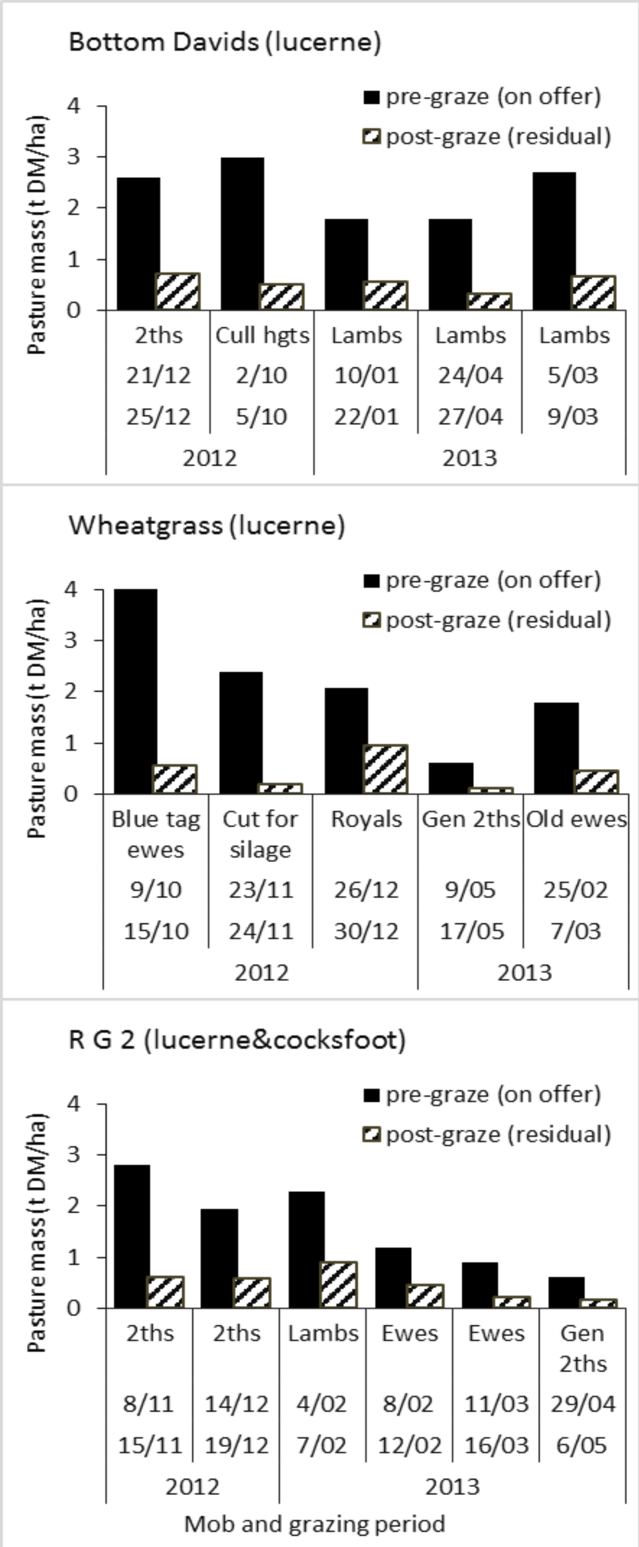

Figure 3 Pre- and post-grazing DM for three paddocks throughout the 2012-13 season detailing the mob shift history. (2ths – 2-tooths; Gen 2ths – General 2-tooths)

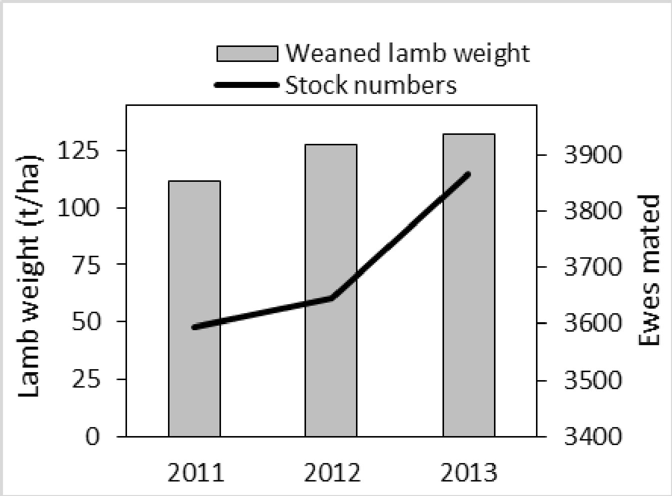

Figure 4 The number of mated ewes and the lamb weaned weight (t/ha) for the 2011/12, 2012/13 and 2013/14 seasons.

2.3 Caucasian clover responses to fertiliser, lime and rhizobial inoculant in rangeland

A.D. BLACK, A.J. HARVEY, J.L. MOIR and D.J. MOOT

Faculty of Agriculture and Life Sciences, Lincoln University, Lincoln, Canterbury

alistair.black@lincoln.ac.nz

Abstract

Caucasian clover was dominant (67–77% of pasture mass) in high country plots which received 0, 100, 200 or 400 kg/ha of superphosphate and 0 or 5 t/ha of lime 10 years after sowing. After 12 years Caucasian clover continued to survive without fertiliser and lime on the infertile acid soil (Olsen P of 5 mg/L, pH of 5.5), but it required 200–400 kg/ha of superphosphate and 5 t/ha of lime to thrive. Biomass of Caucasian clover rhizomes and roots in the top 0.10 m of soil amounted to 5.1 t DM/ha. In another trial, Caucasian clover direct drilled into an infertile, depleted tussock pasture established better with 20 kg N/ha applied at sowing (100 kg/ha of Cropmaster 20) than without N (110 kg/ha of superphosphate), but all plants were N deficient by the following spring. The same soil was tested for nodulation and growth of Caucasian clover in a glasshouse. Most plants were lightly nodulated and all plants were 17–24% the size of plants inoculated with commercial rhizobial inoculant (CC283b) indicating that the N deficiency of field plants was likely due to ineffective inoculation.

Keywords: high country, nitrogen, phosphorus, *Trifolium ambiguum*

Introduction

Pasture improvement by introducing white clover (*Trifolium repens* L.), red clover (*T. pratense* L.) and lucerne (*Medicago sativa* L.) into high country rangelands of New Zealand requires lime and regular inputs of phosphorus (P) and sulphur (S) fertilisers otherwise the legumes do not persist on the infertile acid soils found in these regions (White 1995). Caucasian clover (*T. ambiguum* M. Bieb) has been proven to be very persistent with lower inputs on these extensive grassland sites (Allan & Keoghan 1994; Scott 1998; Strachan *et al.* 1994; Woodman *et al.* 1992). However, like most clovers (*Trifolium* species), Caucasian clover requires reasonably high soil fertility for optimum growth (Black *et al.* 2007; Scott 1998).

Caucasian clover is very slow to establish and therefore susceptible to plant competition during its first year (Black *et al.* 2006a, b). Previous attempts to introduce Caucasian clover into tussock grasslands via broadcast and sod seeding showed that a low rate (100–150 kg/ha) of starter superphosphate (containing P and S) was necessary to facilitate rapid growth of seedlings (Lucas *et al.* 1980; Moorhead *et al.* 1994). Growers have recently refined methods to suppress existing pasture species and place starter fertilisers close to the seed to enable establishment of legumes. In addition, studies have found that, in contrast to common pasture legumes, Caucasian clover fixes little nitrogen (N) during its first year when inoculated with currently available commercial inoculant (Seguin *et al.* 2001), and therefore may be N deficient during establishment in infertile high country soils.

Because of Caucasian clover's persistence in rangeland, a series of three experiments were carried out in which the objectives were to:

1) determine the rate of superphosphate required to maximise the dry matter production of a mature pasture of Caucasian clover in the high country
2) determine if N in starter fertiliser can improve the establishment of Caucasian clover and cocksfoot when direct drilled into undeveloped ("native") tussock grassland
3) examine the same soil used for Objective 2 for nodulation and growth of Caucasian clover plants in the absence and presence of fertiliser and lime in a glasshouse

Methods

First field experiment

This experiment was set up in an established pasture of Caucasian clover at Lake Heron Station, Mid Canterbury, New Zealand (43°23'31.47"S, 171°9'5.89"E) on an upland yellow brown earth. The site is 680 m above sea level with an estimated annual rainfall of 900 mm, although summer droughts and dry winds are common on the flat and exposed site. The pasture was mostly Caucasian clover (cv. Endura), which was drilled in 2002, and very low producing browntop (*Agrostis capilaris* L.). There had been no fertiliser inputs since an application of 150 kg/ha of superphosphate at sowing. An initial soil test indicated moderate acidity (pH 5.5) and as a result aluminium (Al) was moderate, approaching toxic levels (1.7 mg/kg). Phosphorus was very low (Olsen P 5 mg/L) but S (sulphate S 11 mg/kg), magnesium (Quick Test Mg 10) and potassium (QT K 8) were adequate.

Superphosphate (9% P and 12% S) was broadcast at four rates (0, 100, 200 and 400 kg/ha) in the absence and presence of lime (5 t/ha) in February 2012, according to a 4 × 2 factorial in a randomised block design with four blocks of eight 12 × 20 m plots.

Pasture production and Caucasian clover content were measured on 28 November 2012 and 21 November 2013 in a random site in each plot. At each site a 5 × 0.46 m strip was mown to 2 cm above ground. The sample was then weighed and a 100 g subsample dried at 70°C to determine dry matter (DM) content, which was applied to whole sample fresh weight to calculate the total pasture yield (kg DM/ha). Another sample was clipped from beside the mown strip, botanically separated and dried at 70°C to determine the percentage of Caucasian clover. Plots were also observed for pasture production on 14 April 2012, 22 March 2013 and 19 March 2014, but on each occasion the pasture was only 2–3 cm tall due to limited soil moisture and thus impractical to harvest. Plots were grazed with Merino sheep for 2–3 days soon after the November harvests and in April or May of each season.

On 9 May and 28 November 2012, leaf plus petiole samples of Caucasian clover were taken from each plot for mineral analysis at Lincoln University. Also in November, soil cores (0–7.5 cm depth) were taken from each plot and bulked on treatment for nutrient analysis.

On 19 March 2014, a 0.38 × 0.38 m quadrat was dug to a depth of 0.10 m at a random site in each of the plots with the lowest and highest rates of fertiliser and lime. Caucasian clover was separated from other species, washed, assessed for taproots and shoot growing points, and then dried at 70°C to determine the biomass of rhizomes and roots.

Second field experiment

The second experiment was established in an undeveloped ("native") pasture at Lake Heron Station (43°29'27.08"S, 171°13'11.61"E) on a similar soil to the previous site (pH 5.5, Al 2.1 mg/kg, Olsen P 7 mg/L, sulphate S 14 mg/kg, QT Mg 16, QT K 10). This site is 765 m above sea level, flat and with an estimated annual rainfall of 700–800 mm. The pasture was depleted fescue tussock (*Festuca novae-zelandiae* (Hack) Ckn.) dominated by low producing browntop, Kentucky bluegrass (*Poa pratensis* L.) and sweet vernal (*Anthoxanthum odoratum* L.) grasses and mouse-ear hawkweed (*Hieracium pilosella* L.) with very low (< 1%) legume content and up to 30% bare ground. The site has had no regular fertiliser and lime inputs.

The pasture was sprayed with glyphosate (2 L/ha), grazed by sheep and then divided into six large plots (~2 ha) in preparation for sowing. On 20 December 2011, the plots were drilled with a seed mix of Caucasian clover cv. Endura (6 kg/ha of commercially inoculated coated seed) and cocksfoot cv. Vision (2 kg/ha) and one of two fertilisers using a Duncan Enviro 3000E triple disc drill, according to a randomised block design with three replicates. The two fertilisers were superphosphate (9% P and 12% S) at 110 kg/ha and Cropmaster 20 (20% N, 10% P and 12.5% S) at 100 kg/ha. Hence all plots received the same rates of P (10 kg/ha) and S (12.5 kg/ha), but the Cropmaster 20 plots received an additional 20 kg/ha of N. More P (20 kg/ha) and S (50 kg/ha) was applied to all plots as Sulphur Super 20 (250 kg/ha) in February 2012. The pasture was not grazed or fertilised over the following 12 months.

Plant establishment was measured on 7 March and 28 November 2012 in five random 2 m lengths of drill row in each plot. Each row was dug to 0.10 m depth and assessed for plant population, shoot weight and nodulation on the first measurement date and for population and shoot weight on the second date.

Glasshouse experiment

The glasshouse experiment was set up as a 2 × 3 × 2 factorial in a randomised block design with four replicates and 1.3 L plastic pots. Treatments were all possible combinations of the presence and absence of lime, either superphosphate or nutrient solution, and inoculant.

Soil (0–0.2 m depth) was collected from a site next to where the second field experiment was situated in March 2013. The soil was mixed, sieved and analysed: pH 5.4, Olsen P 7 mg/L, Mg 0.37 me/100 g, K 0.37 me/100 g, sulphate S 9 mg/kg and Al 6.4 mg/kg. It was then mixed with the appropriate rates of lime and superphosphate and placed into pots. The equivalent to 3 t/ha of lime (2.8 g of calcium carbonate/pot) and 200 kg/ha of superphosphate (1.1 g of monobasic phosphate monohydrate and 0.5 g of gypsum/pot) were used. Nutrient solution, which contained P, S, Mg, K, Ca and micro-nutrients, was applied at 70 mL/pot every 2-3 weeks after sowing. Caucasian clover cv. Endura seeds were inoculated before sowing with a moist peat formulation called Nodulaid®, which contained a culture of rhizobia strain CC283b recommended for Caucasian clover (Becker Underwood, Australia).

Pots were watered with tap water every 1–2 days. Plants were gradually thinned to three per plot. The remaining plants were harvested 19 weeks after sowing and assessed for shoot and root dry weights and root nodules. Bulk foliage of inoculated plants and soil samples from each lime × fertiliser treatment were then subjected to mineral analyses.

All response variables were tested for treatment effects by analysis of variance according to the experimental designs using Genstat 16 statistical software.

Results and Discussion

First field experiment

The Caucasian clover used in this experiment had persisted and spread by underground rhizomes in the presence of sheep grazing, summer droughts and no fertiliser inputs since sowing to become the dominant species after 10 years. This result confirmed that Caucasian clover can provide a strong legume base for pasture production in rangeland (Woodman *et al.* 1992). However, the abundance of browntop and soil test results indicated that P, perhaps in combination with pH and Al issues, was likely to limit growth of Caucasian clover, and as a result pasture production responded to all rates (100–400 kg/ha) of superphosphate.

Averaged over the 2 years, pasture production in November increased ($P<0.08$) with rate of superphosphate irrespective of the absence and presence of lime (Figure 1). The lime appeared to increase pasture production only when superphosphate was applied, although this effect was not significant ($P<0.90$). The contribution of Caucasian clover, expressed as a percentage of pasture production, was not affected by superphosphate and lime, and averaged 67–77%. Caucasian clover growth was therefore responsive to all rates of superphosphate, but 400 kg/ha and lime were required to achieve the maximum pasture yield.

Phosphorus, S and N contents in the Caucasian clover samples increased ($P<0.05$) with increasing rates of superphosphate (Table 1). However, the levels are below those found for Caucasian clover on higher fertility soil (Black *et al.* 2007), and below optimum values for most pasture species (Cornforth & Sinclair 1982). Soil Olsen P and sulphate S levels were close to adequate in all treatments (Table 1). Lime raised the pH from 5.5 to 6.0 and lowered Al from 2.4 to 0.6 mg/kg. These results suggest that a higher rate of superphosphate may be required for maximum growth of Caucasian clover at this site.

The growing point population of Caucasian clover with 400 kg/ha of superphosphate and lime was higher ($P<0.06$) than it was without superphosphate and lime (Table 2), which helps explain the greater spring yields. The taproot population was 9/m^2 and the biomass of rhizomes and roots in the topsoil was ~5 t DM/ha for both treatments. This large rhizome and root mass is consistent with that found by Strachan *et al*. (1994) and may explain why Caucasian clover plants are able to survive on infertile soils in extreme climates. However, the lack of taproots was not expected and maybe one reason why the Caucasian clover showed signs of moisture stress in early summer of each season.

Therefore overall these field results indicate that Caucasian clover survived for 12 years on the infertile high country soil without any fertiliser inputs after sowing, but it required 200–400 kg/ha of superphosphate and 5 t/ha of lime to thrive.

Second field experiment

After 11 weeks, plant populations were not affected by starter N and all Caucasian clover plants sampled were poorly nodulated (Table 3). However, growth of Caucasian clover and cocksfoot with starter N fertiliser was greater ($P<0.01$) than that of the control. After 11 months, shoots of all Caucasian clover plants were no bigger than 4 mg and showed signs of chlorosis. Cocksfoot shoots with N were three times the size of those without N, and were substantially heavier than Caucasian clover shoots. These results indicate that Cropmaster 20 enabled better establishment of cocksfoot than superphosphate due to the N applied. However, neither fertiliser enabled establishment of Caucasian clover. Its seedlings appeared deficient in N which suggests they fixed little N despite being inoculated.

Possible causes of the N deficiency are 1) that rhizobia that nodulate Caucasian clover are not present in the soil and 2) that the populations of live and effective rhizobia on the coated seeds were below standard. Both explanations are in agreement with Pryor *et al.* (1998), which stated that Caucasian clover will not form functional nodules in New Zealand soils without fresh and effective rhizobial inoculum. In addition, the effectiveness of the inoculant used in this trial may have been impeded by soil fertility. The glasshouse experiment was therefore required to test the same soil for nodulation and growth of Caucasian clover plants in the absence and presence of fertiliser and lime.

Glasshouse experiment

All Caucasian clover plants grown from inoculated seed were nodulated (Figure 2) and foliar N was optimal (Table 4) regardless of fertiliser and lime, indicating the commercial rhizobial inoculant (CC283b) was effective. Growth of inoculated plants with fertiliser was greater than those without fertiliser, due to higher foliar P, but only with lime (Figure 3). The limed soil was adequate in pH (6.2) and Al (<0.5 mg/kg) whereas the un-limed soil was low in pH (5.5) and high in Al (4.4 mg/kg), which suppressed growth of Caucasian clover. These results are consistent with the superphosphate × lime response in the first field experiment.

In contrast, most Caucasian clover plants (24 of 36) grown from un-inoculated seed were lightly nodulated (Figure 2) and all plants were 17–24% the size of the inoculated plants regardless of fertiliser and lime treatment (Figure 3). These results indicate that rhizobia that nodulate Caucasian clover are not present in the soil from Lake Heron Station (Pryor *et al.* 1998). Therefore, the N deficiency of Caucasian clover plants in the second field experiment was likely due to ineffective inoculation which, possibly in combination with Al issues, impeded establishment.

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List of Figures and Tables

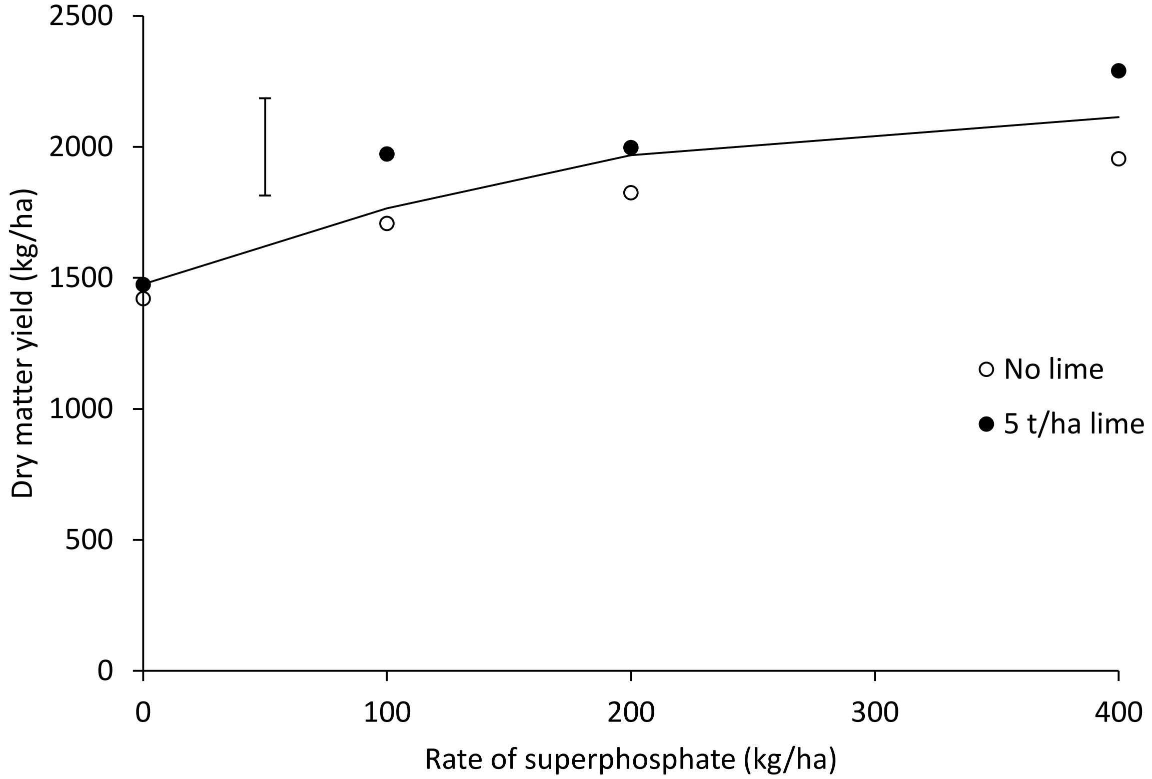

Figure 1 Effect of rates of superphosphate and lime on dry matter production of established Caucasian clover pasture in November, averaged over 2 years. Bar indicates SED.

Table 1 Effect of rates of superphosphate on foliage and soil (0–7.5 cm) mineral concentrations for the first field experiment.

	Rate of superphosphate (kg/ha)					
	0	100	200	400	P value	SED
			Foliage			
P%	0.197	0.198	0.212	0.240	<0.001	0.0064
S%	0.174	0.172	0.177	0.184	0.040	0.0040
N%	3.418	3.367	3.510	3.612	0.002	0.0640
			Soil			
Olsen P (mg/L)	11	11	11	14	-	-
Sulphate S (mg/kg)	8	10	9	10	-	-

Table 2 Effect of absence and presence of superphosphate (400 kg/ha) and lime (5 t/ha) on populations of shoot growing points and taproots, and biomass of rhizomes and roots of Caucasian clover excavated to 0.10 m depth in March 2014.

	Superphosphate and lime			
	Absent	Present	P value	SED
Shoot growing points/m^2	1338	1901	0.063	194.8
Taproots/m^2	9	9	1.000	2.8
Rhizomes/roots (kg DM/ha)	4818	5343	0.632	987.7

Table 3 Effect of starter nitrogen fertiliser on seedling establishment of Caucasian clover (Cc) and cocksfoot (Cf) in March 2012 (11 weeks after sowing) and November 2012 (11 months after sowing).

		Starter nitrogen (kg/ha)		P value	SED
		0	20		
		11 weeks after sowing			
Plants/2 m	Cc	12.9	12.2	NS	2.37
	Cf	14.3	12.2	NS	4.32
Shoot dry weight (mg)	Cc	5.9	17.3	<0.01	3.61
	Cf	9.1	53.5	<0.001	7.23
Nodulation[†]	Cc	1.05	1.18	<0.05	0.056
		11 months after sowing			
Plants/2 m	Cc	7.5	13.5	NS	6.24
	Cf	29.0	39.2	NS	6.70
Shoot dry weight (mg)	Cc	2.0	4.0	NS	1.52
	Cf	60.0	199.0	NS	76.20

[†]1 = no nodules, 5 = abundant nodules

Table 4 Effects of absence and presence of either superphosphate (SP) or nutrient solution (All) on mineral concentrations in foliage from inoculated Caucasian clover plants and soil in the glasshouse experiment.

	Nutrient treatment		
	Nil	SP	All
		Foliage	
P%	0.274	0.366	0.316
S%	0.280	0.253	0.251
N%	4.403	4.395	4.594
		Soil	
Olsen P (mg/L)	5	37	10
Sulphate S (mg/kg)	14	99	35

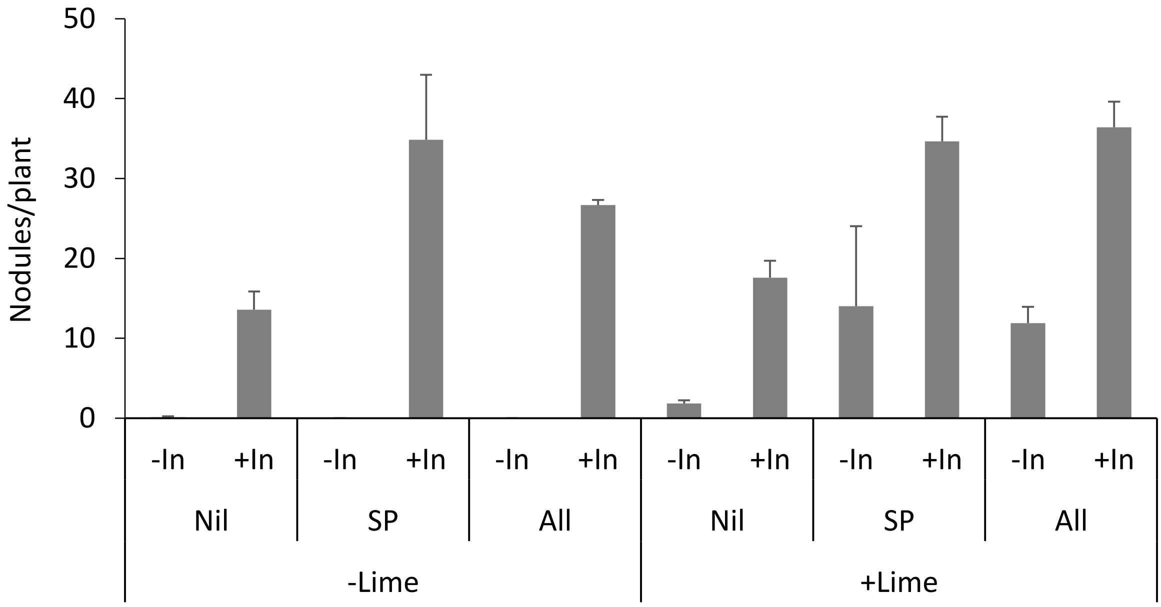

Figure 2 Effect of rhizobial inoculant (In) CC283b on nodulation of Caucasian clover plants grown in soil from the second field experiment in the absence and presence of lime and either superphosphate (SP) or nutrient solution (All) in a glasshouse. Bars are SEMs.

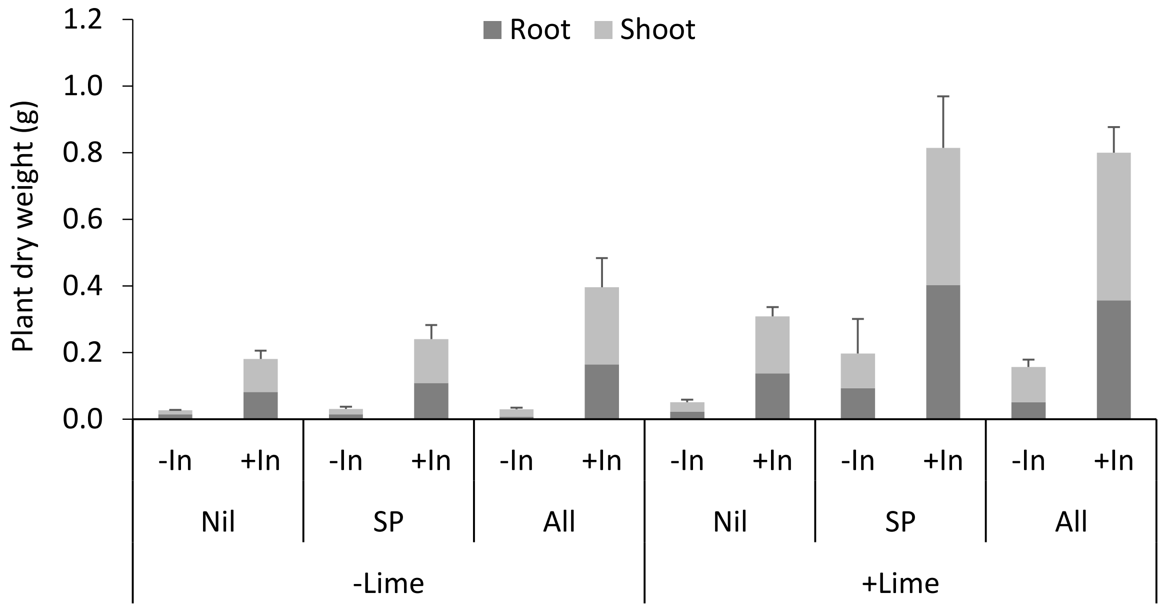

Figure 3 Effect of rhizobial inoculant (In) CC283b on growth of Caucasian clover plants grown in soil from the second field experiment in the absence and presence of lime and either superphosphate (SP) or nutrient solution (All) in a glasshouse. Bars are SEMs.

2.4 Medium-term soil pH and exchangeable aluminium response to liming at three high country locations

J.L. MOIR[1] and D.J. MOOT[2]

[1]*Department of Soil and Physical Sciences*

[2]*Department of Agricultural Sciences*

Lincoln University, PO Box 84, Lincoln, Canterbury

jim.moir@lincoln.ac.nz

Abstract

Acid soil conditions and associated aluminium (Al) toxicity pose a serious impediment to legume establishment, persistence and productivity in high country. However, data that report soil exchangeable Al levels in response to lime applications are scarce. Three historical (3-8 year old) lime trial soils were sampled in terms of soil pH and exchangeable aluminium (Al). Soil pH ranged from 4.8 to 7.5, with exchangeable Al levels ($CaCl_2$ extraction) of 0.2 to 24 mg Al/kg. Soil pH and exchangeable Al changed significantly when lime was applied but the shape of the response differed between the three site locations. The soil pH changes (0-7.5 cm horizon) were 0.16, 0.10 and 0.20 pH units/t lime applied.Critical research needs to be conducted to investigate the key soil factors and mechanisms that result in Al toxicity in high country soils to enable development of mitigation strategies. On-farm decisions on lime rates and legume species suitability need to be based on soil pH and Al testing from individual farm blocks rather than using ‘rule of thumb’ approaches.

Keywords: soil pH, soil exchangeable aluminium, lime, pasture legumes

Introduction

Many South Island high country soils have low soil pH and possibly high soil Al. Soil acidity (low soil pH coupled with toxic levels of soil aluminium) and low available phosphorus (P) and sulphur (S) may also limit establishment and maintenance of legumes (Moir *et al*. 2000; Haynes & Williams 1993). To offset increased soil acidity, lime must be applied, and where this cannot be done economically, soils may be too acidic for legumes and productivity declines sharply (Edmeades *et al.* 1983; Lanyon & Griffith 1988). Valuable dryland forages, such as lucerne (*Medicago sativa* L.), are intolerant of acid soil conditions, and related aluminium (Al) toxicity (Rechcigl *et al.* 1988; Su & Evans 1996). Often the cost of lime or its application is uneconomic in extensive high country regions. In many cases the rate of penetration of the effects of surface applied lime, and subsequent pasture response, are unknown. Incorporation of lime may be a possible on flatter land but the risk of wind erosion means direct drilling is the preferred establishment technique. The relationship between pasture production and soil pH is well established on some high country soils and the critical level of soil Al (Haynes & Williams 1993) and the relative Al tolerance of some forage legumes have also been examined (Edmeades *et al.* 1991; Wheeler *et al.* 1992). However, studies of soil pH changes with surface applied lime, and associated changes in soil exchangeable Al at the surface and at depth over time, in South Island high country soils are scarce.

Previously, Moir and Moot (2010) reported on the effects of surface applied lime on lucerne in an acid high country soil. Horizontal, restricted, root growth related to Al toxicity issues were reported, along with soil pH and exchangeable Al changes resulting from lime applications. This paper reports updates results from a from this field experiment and also reports results from two additional established lime trials in the South Island high country. The aim of this study was to examine the effects of lime rate on pH and soil exchangeable aluminium levels of three acid high country soils at different locations.

Methods

Site description and trial design

Three historical lime field trials were examined. Site 1 was located at Mt Pember station, North Canterbury (Moir *et al.* 2010); Site 2 was Glenmore station, located on the southern banks of Lake Tekapo, central Canterbury; and Site 3 was Glenfoyle station, near lake Hawea, Central Otago. Site specific information and treatment lime rates are presented in Table 1.

AgLime was surface applied at Site 1 in March 2008, followed by sowing of 'Grasslands Kaituna' lucerne . Further details of the Mt Pember Station experimental area are given by Moir and Moot (2010) and Fasi *et al.* (2008). All plots were soil sampled to 15 cm depth in September 2013. Glenmore Station (Site 2) is a pasture experimental site being used for for high country research (Moot *et al*. 2014). AgLime was surface applied in replicate blocks (20x10 m plots; 2 replicates) in October 2010 and soil samples (30 x 2.5 cm cores; 0-15cm deep) were taken in March 2013. Glenfoyle Station (Site 3) consists of medium (5x10m) pasture plots on hill slopes with treatments replicated four times (Espie, 2008). AgLime was surface applied in April 2005 and soil samples (15 x 2.5 cm cores; 0-15 cm or 0-7.5 cm deep in stony ground) taken in December 2012. All soil samples were analysed for pH (1:2.5 soil: water ratio) and exchangeable aluminium (0.02M $CaCl_2$ extraction followed by ICP-OES analysis).

Results

Lime effects on soil pH

Soil pH differed with horizon depth and lime rate at all three sites. At Site 1 (Mt Pember Station), soil pH was higher at 0-7.5 cm than the 7.5 to 15 cm, five years after the initial application. The pH in the 0-7.5 cm horizon increased in a linear fashion with lime , to a maximum of 6.7 at 8 t lime/ha (Table 2). In the 7.5-15 cm horizon, pH was unaffected by lime rate, except at 8 t/ha, where it increased to 6.1. At Site 2 (Glenmore station), moderate increases in soil pH were observed in the 0-7.5 cm horizon three years after lime was applied, but not in the 7.5-15 cm horizon. At Site 3 (Glenfoyle Station), large increases in soil pH occurred in the 0 -7.5 cm horizon in response to lime applications eight years after application. The maximum increase was 0.8 pH units at 4 t lime/ha. Only minimal increases in pH were observed with increasing lime rate for the 7.5-15 cm horizon at this site. In terms of soil pH change per unit of lime applied, changes for the 0-7.5 cm horizon were 0.16, 0.10 and 0.20 pH units/t lime applied at Sites 1, 2 and 3 respectively.

Lime effects on soil aluminium levels

Soil Exchangeable Al levels were strongly affected by lime rate. Comparing the highest lime rate at each site, soil exchangeable Al dropped by 2.5, 2.4 and 2.0 mg Al/kg at Sites 1, 2 and 3, respectively for the 0-7.5 cm horizon. In the 7.5-15 cm horizon, changes in exchangeable Al levels were minimal, except at the oldest Site 3, where 4 t lime/ha caused a reduction of 8.1 mg Al/kg.

Relationships between soil pH and exchangeable aluminium

Over all soil sampling depths and liming rates, soil pH was strongly associated with soil exchangeable Al levels at all sites (Fig. 1). Exponential curves were appropriate to describe the relationships at sites 1 (R^2=0.85) and 3 (R^2=0.83), but a polynomial curve was required at site 2 (R^2=0.69). Soil exchangeable Al was low (1-2 mg/kg) within the soil pH range of 6.0-7.0. However, exchangeable Al levels rose sharply to 2-3 me/100g when pH fell below 5.7. At a pH of 5.5, exchangeable Al increased to 5.0, 2.5 and 4.0 mg/kg at sites 1, 2 and 3 respectively. Increases in exchangeable Al below pH 5.5 were near linear at sites 1 and 3, increasing at 3-4 mg Al/kg per 0.1 pH unit decrease in pH. At site 2, increases in exchangeable Al below pH 5.5 were 1 mg Al/kg per 0.1 pH unit decrease in pH.

Discussion

Thhis study has determined the effects of historic liming on soil pH at three high country locations, and in turn, on exchangeable Al, in two surface soil horizons. Strong relationships between soil pH and exchangeable plant-available Al were established for these soils, whereby soil exchangeable Al increased exponentially below a soil pH of 5.7. The ‘change points’ on the curves for Sites 1 and 3 are strong evidence that these soils are very sensitive to pH change. Importantly,below pH 5.7, Al levels increase rapidly to levels that are toxic to many legumes. This result generally agrees with that reported by Hochman *et al.* (1992) for three New Zealand Brown soils, but does not follow in soils of different age and mineralogy. For example, Mullen *et al.* (2006) reported low exchangeable Al of 1.3 mg/kg at pH 4.4 ($CaCl_2$) in a soil (Red Chromosol, granitic parent material) in NSW. Our results also highlight the problem of higher soil-exchangeable plant-available aluminium levels (at ‘typical’ field soil pHs) in Brown soils, which are common to South Island high country. Also notewothy, is the variable relationship between soil exchangeable Al and soil pH, and that relationships between these indices appear to be soil or site specific. Further detailed research is required to determine the key mechanisms driving the site-to-site variations in these relationships.

Liming had a strong medium-term effect on soil pH at all three sites, especially in the 0-7.5 cm soil horizon. Soil pH increased an average of 0.16 units/t lime applied. This result agrees with Wheeler & Edmeades (1995) and Black & Cameron (1984). Liming reduced soil exchangeable Al levels in the surface soil horizon by 2.0-2.5 mg/kg, even after 3-7 years post application. This result, demonstrates that exchangeable Al at the soil surface can be reduced to safe levels, even several years after lime application. At a soil pH of 5.5, exchangeable Al increased to 3.0 mg/kg or above. At this level, exchangeable Al is likely to reduce DM yield (Wheeler *et al.* 1992, Moir and Moot 2010). As such, on-farm decisions on lime rates and legume species suitability need to be based on soil pH and Al testing from individual farm blocks rather than using ‘rule of thumb’ approaches across farms.

The measurable effects of lime were less obvious in the deeper soil horizon, with only modest changes in soil pH and exchangeable Al. At site 1 Lime at 8 t/ha increased soil pH by about 0.5 pH units in the 7.5-15 soil horizon, but not at lower lime rates. This increase in soil pH resulted in a corrresponding drop in exchangeable soil Al from 5.6 to 1.9 mg/kg. Importantly, this reduction in Al represents a change to non-toxic levels in the 7.5-15 cm horizon at Site 1, five years after the initial application. This contrasts the earlier measurements at this site (Moir and Moot 2010), and reinforces the importance of running trials for longer time spans to determine the longer-term effects of climate and its variability on the response to lime in these high country environments. Interestingly, no soil pH or Al changes occurred in the 7.5-15 cm horizon at Site 2 as a result of liming. This is the youngest site and mirrors the lack of response in this horizon previously seen at Site 1. Futher monitoring will continue at this site. The implication is that even at a rate of 5 t/ha, surface-applied lime is unlikely to reduce plant-available soil aluminum to safe levels for legume growth in the 7.5-15 cm horizon at Site 2 within three years. Thus, the application of lime should occur prior to three years of winter forage, crops such as ryecorn, to break down the resident vegetation. However, even this may be insufficient to allow the successful establishment of aluminium senstive legumes and alternatives such as *Lupinus polyphyllus* may be required (Moot *et al*. 2014) As it stands, plant root depth and therefore available water content of the soil are likely be compromised at Site 2, which impacts on yield and persistence (Mullen *et al.* 2006, McGowan *et al.* 2003, Teixeira *et al.* 2006,Grewal & Williams 2003). At Site 3, Al levels were reduded to 'safe' levels at lime rates of 1t/ha and above in the 0-7.5 cm horizon. However, background Al were much higher in the 7.5-15 cm horizon at this site. As such, although Al was substantially reduced in the deeper horizon (again, by lime rates of 1 t/ha and above), Al levels were still around 10 mg/kg, and so remained toxic to most pasture legumes. These very high Al levels in the 7.5-15 cm horizon at Site 3 contrasts with that of the other two sites in this study, and highlights the variability of soil exchangeable Al due site specific factors, which are currently poorly understood. This study has highlighted the importance of conducting longer-term soil measurements in order to develop a fuller understanding of the effects of lime. Repeated measurements in a time sequence are therefore required to improve our understanding. Critically, considerable further reserach is required to explain the key factors driving variability in soil exchangeable Al levels.

Conclusions

- Soil pH was strongly related to levels of soil exchangeable Al.
- Surface applied lime increased soil pH and reduced soil exchangeable aluminium, especially at higher lime rates.
- Surface applied lime took 5-8 years to produce observable changes in the 7.5-15 cm zone.
- The effect of lime on soil pH and exchangeable Al varied between sites, which highlights the lack of current understanding of mechanisms driving soil Al levels.
- On-farm decisions on lime rates and legume species suitability need to be based on soil pH and Al testing from individual farm blocks rather than using 'rule of thumb' approaches.

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Table 1 Site physical information and treatment lime rates for three historical high country field trials.

Site	Location	Annual Rainfall (mm)	Altitude (masl)	Topography	Soil Group	Lime Rates (t/ha)
1: Mt Pember Station	North Canterbury	600	430	Flat	Stony Brown Soil	0, 2, 4, 8
2: Glenmore Station	Central Canterbury	600	700	Flat - rolling	Brown soil	0, 3, 5
3: Glenfoyle Station	Central Otago	600	750	Hill (15-20º)	Dense brown hill soil	0, 0.13, 0.25, 0.5, 2, 4

Table 2 Soil pH and exchangeable Al values for three high country field trial sites at two soil horizon sampling depths (0-7.5 and 7.5-15 cm).

Site	Lime Rate (t/ha)	pH		Exchangeable Al (mg/kg)	
		0-7.5 cm	7.5-15 cm	0-7.5 cm	7.5-15 cm
1: Mt Pember Station	0	5.4	5.6	3.0	5.6
	2	5.7	5.7	2.2	4.4
	4	6.1	5.6	1.2	5.5
	8	6.7	6.1	0.5	1.9
	sem	*0.09*	*0.12*	*0.20*	*1.40*
2: Glenmore Station	0	4.9	5.3	5.0	5.1
	3	5.5	5.2	2.2	5.9
	5	5.4	5.2	2.6	4.9
	sem	*0.05*	*0.04*	*0.82*	*0.80*
3: Glenfoyle Station	0	5.5	5.2	3.1	17.3
	0.13	5.6	5.1	3.5	17.4
	0.25	5.6	5.3	3.0	13.0
	0.5	5.6	5.3	3.9	13.5
	1.0	5.8	5.3	1.5	9.8
	2.0	6.0	5.3	1.4	11.8
	4.0	6.3	5.3	1.1	9.2
	sem	*0.11*	*0.03*	*0.90*	*0.91*

2.5 Sheep performance on perennial lupins at Sawdon Station

This paper was included in the 18-month report by PhD student, Travis Ryan-Salter, on page 48 of this report.

2.6 Identification and effectiveness of rhizobial strains that nodulate *Lupinus polyphyllus*

This paper was included in the 18-month report by PhD student, Travis Ryan-Salter, on page 59 of this report.