Soil pH, exchangeable aluminium and legume yield responses to deep-placed lime at Omarama Station

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Abstract
The passive moment of lime down the soil profile in dryland is slow so a machine was developed to directly inject lime into soil, and was tested it at Omarama Station. Pelleted lime was injected at simultaneous depths of 5-10 cm and 20-25 cm below the soil surface at rates of 0 (control), 500, 1000, and 2000 kg/ha and these treatments were compared with 1000 kg/ha of surface-applied pelleted lime. The growth of lucerne, 'Russell' lupins and festulolium was recorded over 3 years. The deep-placed lime increased soil pH and reduced Al levels at soil depths of 25 and 30 cm, whereas for the surface-applied lime this was only the case in the top 7.5 cm of the soil. The deep-placed lime increased the growth of lucerne in the second and third years of the experiment. The lucerne was out-yielded by 'Russell' lupins in each year, which were unaffected by the application of lime.

Keywords: aluminium toxicity, *Festulolium branuii,* injected lime, lime ripper, *Lupinus polyphyllus*, *Medicago sativa*.

Introduction
Toxic levels of exchangeable aluminium (Al) occur extensively in the acid soils of the South Island hill and high-country (Moir & Moot 2014; Whitley *et al.* 2016). Al is particularly toxic to legumes which are relied upon in the hill and high-country for nitrogen fixation and quality feed (Scott 2003). Al toxicity impedes root growth, damages root caps and root hairs, inhibits nodulation and reduces the ability of plants to extract water and nutrients from soil (Foy *et al.* 1978). Al is prevalent in subsoil layers of hill and high-country soils (Whitley *et al.* 2016) which can limit the rooting depth of legumes.

Al is generally considered to become toxic to legumes at a level of 3.0 mg/kg soil (0.02M $CaCl_2$ extraction) (Edmeades *et al.* 1983). However, the susceptibility of different legumes to Al toxicity differs considerably (Moir *et al.* 2016). Lucerne (*Medicago sativa*) is a deep rooting and drought tolerant legume that produces high quality feed, but it is highly susceptible to Al, and this restricts its use in South Island hill and high-country (Moot & Pollock 2014; Moir *et al.* 2016). Other legumes such as 'Russell' lupins (*Lupinus polyphyllus*) and *Lotus pedunculatus* are more tolerant of low pH and Al and have potential for use in the South Island hill and high-country (Scott 1989; Moot & Pollock 2014; Moir *et al.* 2016).

Lime is required to reduce soil acidity and Al concentration before an Al sensitive crop, such as lucerne, can be successfully grown. However, passive movement of lime down the soil profile is slow, especially in dryland environments (Farina & Channon 1988; Kirchhof *et al.* 1995; Moir & Moot 2014). Conventionally, cultivating lime into soil is also undesirable in many hill and high-country soils due to the risk of wind erosion, soil stoniness, expense, and it has been shown to be ineffective at reducing soil acidity below the depth of cultivation (Farina & Channon 1988; Coventry 1991).

To overcome this problem a prototype machine was developed to deep-place lime by injecting it into subsoil layers with minimal cultivation. The Flexiseeder® lime ripper pneumatically feeds lime from a hopper to two delivery ports behind each of the eight, height and angle adjustable, 30 cm spaced Kverneland ripper tines that are fixed to a custom built frame. Optimise® pelleted lime (CP Lime Solutions Ltd 2015) was used in this experiment due to its consistency of particle size for steady calibration of the machine.

The objective of this study was to determine if injecting lime into an acid subsoil can change the soil pH and allow aluminium sensitive species such as lucerne to be grown successfully. This was done at Omarama Station where the growth of lucerne and 'Russell' lupins was measured over three growing seasons between 2015 and 2018. Comprehensive sampling of the distribution and effects of the applied lime on plant roots, soil pH and Al was carried out in December 2016 and January 2018.

Methods
Site description
The experimental site (OM) was located on the fluvial flats of Omarama Station south of the Omarama township on a Mackenzie shallow loam soil (S-Map

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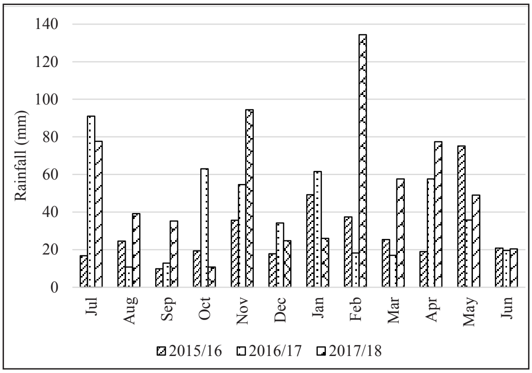

Figure 1 Monthly rainfall at the Omarama Station experimental site 2015-2018.

2015) at location 44˚30'23.60"S 169˚54'16.04"E and at 475 m a.s.l. Before the experiment the site had been in an undeveloped state, supporting mostly browntop (*Agrostis capillaris*), haresfoot clover (*Trifolium arvense*), and hawkweed (*Pilosella officinarum*). For a July to June production year, total rainfall recorded at the site for 2015/2016 was 351 mm, with 472 mm for 2016/2017 and 647 mm for 2017/2018, with the monthly distribution shown in Figure 1.

Pre-treatment, the experimental site was extensively soil core sampled at 0-7.5 cm and 7.5-15 cm depths and the soil chemically analysed (Table 1).

Experimental design

The experiment was initially laid out in a randomised block design with each treatment replicated five times in 25 x 12.5 m blocks, each separated by 6 m. Firstly, ripping to a depth of ~30 cm, Optimise® pelleted lime (90% $CaCO_3$) was directly injected (May 2015) with the eight tine, 2.5 m wide ripper, simultaneously at soil depths of 5-10 cm and 20-25 cm in adjoining 25 m long strips. The lime was injected at rates of 0 (control), 500, 1000, and 2000 kg/ha, along with a separate treatment of 1000 kg/ha of surface-applied (SA) Optimise® lime. Following the lime application the site was heavy rolled and winter-fallowed before being sown in November 2015.

The site was sown perpendicularly to the direction the lime was applied using two adjoining passes of a 2.1 m wide Flexiseeder® plot drill to create 4.2 x 2.5 m plots. 'Force 4' lucerne, 'Russell' lupins, 'Perun' festulolium (*Festulolium braunii*) and two replicates of 'Rahu' ryecorn (*Secale cereale*)/block were sown at 14, 12, 25 and 150 kg viable seed/ha, respectively. The ryecorn was sown as a break-in crop (Anderson *et al.* 2014) and subsequently resown with a second rotation of lucerne and 'Russell' lupins at the beginning of the second year of the experiment (October 2016). Urea was spread on all plots at 40 kg/ha at sowing to assist with the early stages of plant establishment.

In October 2016, at the beginning of the second year of the experiment, the plant treatment strips were halved and overlaid with a low (100 kg/ha) or high (400 kg/ha) rate of 'Sulphur super 30' (0-7-0-30) fertiliser to create a split-plot experimental design with 2.1 x 2.5 m subplots.

Measurements

Herbage yield measurements were carried out three times in the first production year (2015/2016), once in the spring of the second year (2016/2017) and in the spring and autumn of the third year (2017/2018), with an additional lucerne measurement during that summer. The measurement in the second year was of main plots only. After each harvest all plots were mown to a height of 5-10 cm with a sickle bar mower. Sampled herbage had any weeds removed before drying at 65˚C for 48 hours to determine dry matter content and yield.

To investigate the effects of the deep-placed and surface-applied lime treatments on soil pH, Al and root architecture, 40 cm wide by 50 cm deep trenches were dug with a mini-excavator at the boundaries of the lucerne and 'Russell' lupin plots, in December 2016. From each plot all of the roots contained within a 1 m transect were carefully extracted from one drill row adjacent to the edge of the trench. These transects were positioned randomly relative to the location of the 30 cm spaced rip lines. This sampling occurred again in January 2018 when all lucerne plots were sampled but 'Russell' lupins were only sampled from Blocks 1, 3, and 5. The collected root samples were washed and roots of all 'Russell' lupin plants and 10 randomly selected lucerne plants from each sample were

Table 1 Soil test results for the OM experimental site, March 2015.

Depth (cm)	pH[a]	Exch. Al[b] (mg/kg)	Olsen P (µg/ml)	ASC[a] (%)	SO_4-S[c] (µg/g) (	Org-S[c] µg/g)	CEC (me/100g)	BS (%)	C (%)	N (%)
0-7.5	5.3	4.5	16	19	7	4	10	37	2.89	0.24
7.5-15	5.0	8.0								

[a]By method of Blakemore *et al.* (1987).
[b]By method of Edmeades *et al.* (1983) using the 0.02M $CaCl_2$ extraction method.
[c]By method of Watkinson & Kear (1996).

measured for length and scored for nodulation on a 0 (no nodules) to 5 (heavily nodulated) scale and for branching on a 1 (singular taproot) to 5 (highly branched) scale. The samples were then cut into 0-30 cm and >30 cm depth sections and dried at 65°C for 48 hours to determine root dry matter biomass.

Following the root extraction, the walls of the trenches were squared off and a modified 7.5 cm deep soil corer was used to take core samples horizontally into the exposed soil along a 1 m transect. In December 2016, 11 individual soil cores were taken every 10 cm along the 1 m transect from each of the lucerne plots in Blocks 1, 3 and 5 at soil depths of 10 and 20 cm (Figure 2). These were individually analysed for pH and Al to assess the lateral spread of the deep-placed lime within the 1 m transect. These transects were directly in line with where the root sampling had occurred. In January 2018 all lucerne plots were again sampled with six 20 cm spaced core samples taken along the 1 m transect, these core samples were bulked to investigate the cumulative effect of the deep-placed lime across the 1 m transect at sampling depths of 10, 15, 20, 25, and 30 cm below the soil surface. These were analysed for pH and Al (Figure 3). Core samples (7.5 cm deep) were also taken across the surface of the plots.

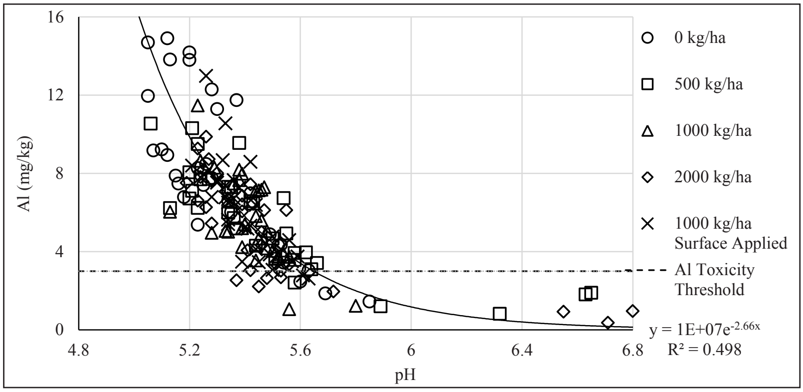

Figure 2 Lime treatment effects on soil pH and Al concentration at 20 cm depth, December 2016.

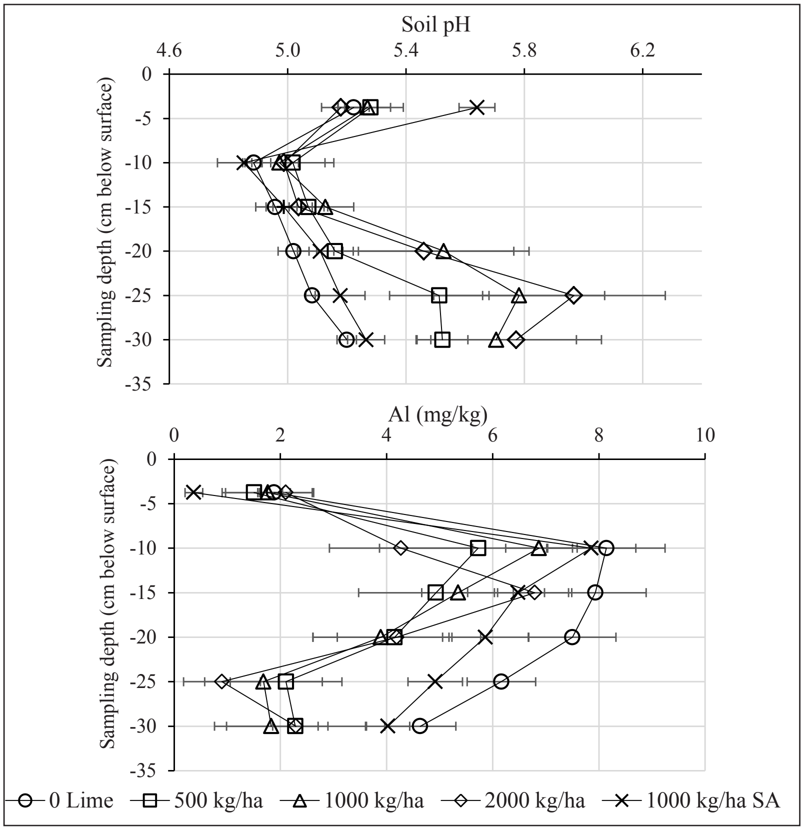

Figure 3 The cumulative effects of lime treatments on soil pH and Al at depth, January 2018.

Before analysis the soil samples were air-dried at 30°C for one week and 2 mm sieved. Soil pH was measured by mixing 10 g of soil in 25 ml de-ionised water (Blakemore *et al.* 1987) and Al by extracting 5 g soil with 10 ml 0.02 M $CaCl_2$, followed by ICP-OES analysis.

Statistical analysis

Before the application of the fertiliser treatment herbage yield and root biomass for individual species, soil pH and Al level were all analysed by one-way ANOVA followed by a Fishers LSD test using Genstat 16. Following the fertiliser application herbage yield was analysed by two-way ANOVA with lime treatment as main plots and fertiliser treatment as subplots, followed by a Fishers LSD test for each plant species. Any effects of the fertiliser treatment on root biomass or soil pH and Al were not considered when doing the trench sampling. Following the two rounds of trench sampling the Al concentrations in the lucerne plots of Block 2 were consistently <0.7 mg/kg at each depth and therefore not consistent with the high Al (>3 mg/kg) in the other blocks. This highlights the variability of the Mackenzie soil across the landscape, so all plant yield, root biomass and soil analysis results from this block have been excluded from the results.

Results

Soil pH and Al level

At the December 2016 soil core sampling Al concentration decreased exponentially as pH increased at 20 cm depth (Figure 2). For the deep-placed lime treatments there was a wide range in pH and Al within treatments and Al toxicity was only alleviated at certain points within each of the 1 m sampling transects. This indicated that there was little lateral distribution of the pelleted lime from the delivery ports of the machine at this depth. Undissolved lime pellets were observed in the soil.

At the 20 cm sampling depth the highest levels of Al (>14 mg/kg) occurred at pH ≤5.2 in the control (0 kg/ha) treatment. By contrast, at pH ≥5.65 Al was reduced to below the 3.0 mg/kg toxicity threshold by the deep application of lime. The 2000 kg/ha deep-placed lime treatment had the most individual sampling points with Al below the 3.0 mg/kg toxicity threshold and, overall, Al was reduced by each of the deep-placed lime treatments compared with the control (P<0.01).

At increased sampling depths in January 2018 the greatest effect of the deep-placed lime occurred below 20 cm (Figure 3).

The deep placement of lime, irrespective of application rate, was successful at increasing (P<0.05) soil pH and reducing (P<0.001) Al to below the toxicity threshold (3 mg/kg) at depths of 25 and 30 cm. At

Table 2 DM yield/ha at Omarama Station in the second and third years of the experiment.

Year			Lucerne	'Russell' lupin	Festulolium	2nd rotation lucerne	2nd rotation 'Russell' lupin
	Lime Rate	0	456	3755	951	-	-
		500	863	3544	1239	-	-
		1000	792	3729	1160	-	-
2016/2017		2000	938	4457	797	-	-
		1000 SA	903	2996	1476	-	-
		SEM	62	642	230	-	-
		$LSD_{5\%}$	192	1361	688	-	-
		P value	***	NS	NS	-	-
2017/2018	Lime Rate	0	942	1691	388	919	1168
		500	1161	2360	507	1154	1458
		1000	1364	2315	402	958	1613
		2000	1478	1942	446	1805	1316
		1000 SA	1195	1551	424	1057	1296
		SEM	97	280	47	203	185
		$LSD_{5\%}$	290	814	136	426	531
	Fert Rate	100	1125	1897	337	950	1457
		400	1331	2046	530	1408	1283
		SEM	62	177	30	128	117
		$LSD_{5\%}$	183	515	86	269	336
	P values	Lime	**	NS	NS	**	NS
		Fert	*	NS	***	**	NS
		Lime x Fert	NS	NS	NS	NS	NS

Significance levels: * P<0.05, ** P<0.01, *** P<0.001, NS not significant depths of less than 25 cm the deep-placed lime had no effect on soil pH and Al compared with the control. The 500 kg/ha deep-placed lime application rate was sufficient to successfully reduce soil Al to below the toxicity threshold, but was not as effective at increasing soil pH as the two higher application rates. The 1000 kg/ha surface- applied (SA) lime treatment increased soil pH ($P<0.001$) and reduced Al ($P<0.001$) in the top 7.5 cm of the soil profile, but had no effect below this depth.

Herbage dry matter yield

Dry matter (DM) yield for the lucerne and 'Russell' lupins was <1000 kg/ha in the establishment year and there was no effects of the lime treatments ($P>0.05$). The ryecorn yielded the greatest at just over 2000 kg/ha, irrespective of lime treatment.

The application of lime, both deep-placed and surface-applied, irrespective of application rate, increased the yield of lucerne over that of the control in 2016/2017 and 2017/2018. The 2000 kg/ha application rate had the greatest effect on lucerne yield, this was the only treatment in the second rotation lucerne to cause an increase in yield in 2017/2018. The 400 kg/ha fertiliser also increased the yield of lucerne and festulolium in 2017/2018 but the yields of both were low. Festulolium yield decreased year on year to the point the plants were mostly dead by April 2018.

The yield of the 'Russell' lupins exceeded that of the lucerne and festulolium in 2016/2017 and was not affected by lime or fertiliser application. By 2017/2018 the yield of the lucerne began to approach that of the 'Russell' lupins. This can be attributed to the continued establishment of the lucerne and a reduction in 'Russell' lupin population from 41.7±6.4 plants/m^2 at the beginning of the experiment to an average of just 4.6±0.7 plants/m^2 by April 2018. The ryecorn break-in crop had no effect on second rotation lucerne and 'Russell' lupin yield.

Root biomass

Plant root biomass to a depth of 30 cm was not affected by lime in either December 2016 ($P=0.97$) or January 2018 ($P=0.86$). The average lucerne root biomass across all lime treatments increased from 1185±280 kg/ha in December 2016 to 1750±212 kg/ha in January 2018. For the 'Russell' lupins it increased from 2630±937 kg/ha in December 2016 to 6050±1855 kg/ha in January 2018. Despite there being no differences in total root biomass more laterally growing lucerne roots were observed in the control (0 kg/ha lime) and surface applied lime plots than in the deep-placed limed plots. Lime treatments had no effect on the degree of branching ($P=0.55$) and plant nodulation ($P=0.91$) of both the lucerne and 'Russell' lupins at the January 2018 sampling. The level of branching in both the lucerne and 'Russell' lupins was 2.6±0.22 and 2.7±0.37 across all lime treatments, respectively. For nodulation the lucerne scored 1.1±0.16 across all lime treatments compared to the 'Russell' lupins at 3.8±0.21.

Discussion

The objective of the experiment was to determine if subsoil acidity and Al toxicity at Omarama Station could be reduced with deep lime placement technology. This was successfully achieved at a depth of 25-30 cm (Figure 3) with the lime delivered from the lower port of the machine. However, the lime delivered from the upper port (5-10 cm below the soil surface) was not effective at reducing acidity and Al toxicity above 25 cm. This is the likely limitation to the growth of the lucerne which will have been impeded by the Al in the intermediate soil layer, and this will have contributed to it failing to successfully nodulate (Berenji *et al.* 2017). The lower delivery port injects lime directly downwards into the void behind the foot of the ripper tine whereas the upper port is angled back slightly, so may have been more effective if it were angled for straight down delivery. Other possible solutions for increasing the effectiveness of the machine above 25 cm could include adjusting the application depths of the two delivery ports, or adding more delivery ports to the machine. A similar machine built by Nelson *et al.* (2012) had four delivery ports behind each ripper tine and the machine built by Farina & Channon (1988) had six. For further development and commercialisation, adding more ports would seem an obvious modification because where the lime was successfully placed at depth, the Al toxicity was alleviated

When considering the lateral distribution of the deep-placed lime the machine created bands of soil where pH was increased and Al reduced, but between these bands the soil was not effectively limed (Figure 2). Correcting soil pH and eliminating Al toxicity in bands down the profile behind the ripper, will allow lucerne roots to grow down them and access more soil water, but is likely to prevent the plants from extracting nutrients from the unlimed soil between the bands creating greater inter-plant competition (Farina & Channon 1988). This was evident in some plots where greater lucerne growth was visible in strips across the plots. To reduce this issue the spacing between the ripper tines could be narrowed or multiple passes of the machine through the soil made.

Despite the poor cumulative effect of the deep-placed lime at reducing Al above 25 cm depth, the yield of lucerne was significantly increased over that of the control treatment in both 2016/2017 and 2017/2018. Root biomass showed no difference between the lime treatments. However, the control and surface-applied lime treatment plots contained a greater proportion of laterally growing roots than the deep-placed lime treated plots which had deeper growing roots. Had the deep-placed lime been more effective in the top 20 cm of the profile the yield and nodulation of the lucerne could have been greater. Implementing the modifications and application methods suggested above could improve the efficiency and economic viability of using the machine to develop stands of lucerne in hill and high-country environments. It is likely that directly injecting lime would be more successful in areas with higher rainfall, where lime pellets dissolve more rapidly.

The yield of the festulolium decreased as the experiment went on, probably due to nitrogen deficiency and its shallow rooting system. This highlighted the importance of growing deep rooting, nitrogen fixing legumes in these dryland environments. Overall, the 'Russell' lupins were the most successful plant at the site. It is likely the lupin density decreased due to the plants being unable to withstand intense mowing of the plots following herbage yield measurements (Moot & Pollock 2014). In a lax grazing system the lupin plant population would be expected to self-govern and higher yields could have been achieved at the site if the plots had not been mown. Unlike lucerne and festulolium the 'Russell' lupins were not affected by either the lime or the fertiliser treatments and were able to successfully nodulate in unlimed soil, highlighting their potential for use in acid, low fertility South Island hill and high-country soils.

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