Soil acidity and aluminium in South Island high and hill-country: new data and future needs

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Abstract
Soil extractable aluminium (Al) concentrations can have a strong impact on the establishment, growth and persistence of pasture legumes. This has become clear in New Zealand high and hill-country, where legumes are scarce and failing to persist in acid soils with high Al levels. For the last decade a research programme has been conducted at Lincoln University focused on legume growth and persistence in acid, high Al concentration soils. Research has examined several aspects of soil acidity and Al toxicity and screened and evaluated a range of legume species, identifying several that show promise in their growth and persistence under acidic and high Al concentrations, in addition to harsh climatic environments. This paper summarises this extensive body of research and also suggests some future research topics for addressing the growing challenge of increasing soil acidity and soil Al faced by increasing numbers of producers.

Keywords: acidic soils, exchangeable soil Al, Al toxicity, legumes

Introduction
Low soil pH and associated high extractable soil aluminium (Al) concentrations have been identified as key factors driving legume presence and performance in some current high and hill-country pastures (Moir & Moot 2014). In combination with harsh seasonal soil moisture extremes, soil extractable Al may indeed be the key edaphic factor negatively impacting on legumes, particularly in high-country environments. As such, soil exchangeable Al poses a major challenge to farmers and indeed the current legume-based pasture system pastoral farmers operate.

The challenge with acidity and in some soils, the associated issue of high Al concentration, is that it is impacting on an ever increasing number of producers, because of the high costs associated with mitigation. The science knowledge base in this research field is disproportionally scarce, because of the lack of urgency and as a consequence, funding for this topic. Previous study has aided the understanding of pH/Al/legume interactions (Edmeades *et al.* 1983, 1991; Wheeler *et al.* 1992; Morton *et al.* 2005; Morton & Moir 2018), but many important questions remain. These include gaps in the understanding of the key factors driving Al concentrations in soil, including variability between soil orders, the exact mechanisms causing plant Al toxicity and how some legumes are able to adapt to or cope with high soil Al. Further, new acid soil/Al tolerant legume forage species are urgently required for these environments, given previous studies (Caradus *et al.* 1986; Mackay *et al*. 1990; Caradus *et al*. 1993) have shown scope for advancing germplasm with increased tolerance and persistence to low fertility acid soils.

New research at Lincoln University in the last decade has focused on improving the understanding of soil acidity and high Al concentrations in high and hill-country environments. Research has included a series of field (Moir & Moot 2010, 2014; Berenji *et al.* 2015, 2017, 2018; Maxwell *et al*. 2016; Whitley *et al.* 2016, Whitley 2018; Whitley *et al.* 2018; Hendrie *et al*. 2018), climate-controlled (Whitley 2013; Schwass 2013; McDonald 2014; Keenan 2014; Rayner 2015; Maxwell *et al.* 2016; Moir *et al.* 2016) and soil survey (Whitley 2018; Che *et al.* 2018) experiments. This programme of work has focused on four key areas:

1. Quantifying the impacts of high Al in soils on pasture/forage legumes
2. Defining soil extractable Al toxicity thresholds for selected legumes
3. Determining key factors which contribute to high Al in New Zealand soils
4. Identification, selecting and testing of Al tolerant legume germplasm.

This paper presents a brief summary of this recent body of work on soil acidity and Al. It is closely aligned with the Lincoln University Dryland Pastures Research team. Some of the results presented here will be reported in more detail in papers from other research team members at the Twizel conference.

Materials and methods
Experimental methods are detailed in the aforementioned publications (see Introduction). General information is presented in Table 1. Some of these publications appear in this Journal issue. Site and soil selections were mostly based on soils with known/documented pH/Al issues. In general, field experiments

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involved replicated plot trials where treatments were applied to long-term pastures or to sown legume species. Sites were mainly commercial high-country farms located in North Canterbury, Tekapo, Omarama and Central and Eastern Otago. Where pasture yield, botanical composition or nutritive value were measured, quadrat cuts were taken on plots before the whole site was grazed by livestock and in a manner typical of the particular farm. Site age ranged from 1 to 20+ years.

For climate controlled (glasshouse) experiments, soils were collected from many high and hill-country farms throughout New Zealand and the experiments were conducted at Lincoln University. Soils examined in these experiments came from Marlborough, North Canterbury, Tekapo, Omarama, Taras, Hawea, Eastern Otago, Waitomo, Taupo and Gisborne. Glasshouse studies focused on the impacts of soil Al concentration on legume growth and the determination of differences between soils and between legumes. The soil Al survey was focused on south Canterbury, examining 21 sites.

Summary of results

Even at high rates of surface applied lime, lucerne can be low yielding, while Al concentration remains high at soil depths below 10 cm. Moir *et al.* (2010) presented results from a medium-term liming trial in North Canterbury utilising lucerne. This work was initiated in response to high-country farmers experiencing widespread failures of lucerne stands, and demonstrated the severe effects of low soil pH and high Al on sensitive legumes such as lucerne. These results prompted an up-scaling of research on acid soils and Al toxicity at Lincoln University, which is continuing today.

Moir *et al.* (2014) revisited some long-term lime-rate trials on pasture. Sites were located in North Canterbury, Tekapo and Central Otago, and had received 0-8 t lime/ha up to 8 years before sampling. Unlimed treatments had up to 24 mg Al/kg soil in the 0-7.5 cm horizon, but limed treatments had low Al levels. However, soil pH was still low below 10 cm, reinforcing again the fact that the liming effect is slow moving and limited below 10 cm in the profile, where lime has been surface applied.

Maxwell *et al.* (2012) examined unsown ‘adventive’ clovers which seem prolific in modern high-country pastures, and compared them to subterranean and white clovers. Following this work, a series of glasshouse

Table 1 General description of soil pH/liming/Al experiments conducted by Lincoln University from 2008-2018.

Study	Experiment type	Location or soil source	Soil orders	Plant (legume) yield	Duration (years)	Research focus
Moir *et al.* (2010)	Field	North Canterbury	Brown	Yes	3	Soil Al, lucerne
Maxwell *et al.* (2012)	Glasshouse	Central Otago	Brown	Yes	1	pH, adventive clovers
Whitley (2013)	Glasshouse	Central Otago	Brown	Yes	1	Al, legume tolerance
Schwass (2013)	Glasshouse	Central Otago	Brown	Yes	1	Al, legume tolerance
Keenan (2014)	Glasshouse	Central Otago	Brown	Yes	1	Al, legume tolerance
McDonald (2014)	Glasshouse	Central Otago	Brown	Yes	1	Al, rhizobia
Moir *et al.* (2014)	Field	Taras, Hawea	Pallic	No	10	pH, Al, liming
Berenji *et al.* (2015)	Field	Nth Canterbury		Yes	5	Al, lupins lucerne, rhizobia
Rayner (2015)	Glasshouse	Omarama, Tekapo, Central Otago	Brown, Pallic	Yes	1	pH, Al, moisture
Maxwell *et al.* (2016)	Field	Central Otago	Pallic	Yes	3	Al, legumes
Moir *et al.* (2016)	Glasshouse	North Canterbury	Brown	Yes	2	Legume Al sensitivity
Berenji *et al.* (2017)	Field	Tekapo	Brown	Yes	5	Al, lupins, lucerne, rhizobia
Whitley *et al.* (2016)	Field	South Canterbury	Brown	No	1	Soil Al
Berenji *et al.* (2018)	Field	Tekapo	Brown	Yes	5	Al, lupins, lucerne, rhizobia
Hendrie *et al.* (2018)	Field	Omarama	Brown	Yes	3	Deep lime placement
Whitley *et al.* (2018)	Field	South Canterbury	Brown	No	1	Legume, Al sensitivity
Whitley (2018)	Field/ Glasshouse	South Island/ North Island	Brown, Pallic, Pumice, Allophanic	Yes	1	Al test, rhizosphere, plant adaptions
Che *et al.* (2018)	Field	Tekapo / Omarama	Brown	No	1-30	Lupins,Al, nitrogen

experiments have examined an array of high acid hill-country soils, with a view to better understand soil Al toxicity, and to determine the potential of known and new legume species to grow in these soils. Lime rates were applied to determine yield response to lime. Maxwell *et al.* (2012) found that adventive clovers seemed adapted to the low fertility, acid, high Al soils, which explained their ability to thrive in the high-country environment. Whitley (2013), Schwass (2013), Keenan (2014), McDonald (2014) and Rayner (2015) all examined a range of pasture and forage legumes as potential new species for high-country. Of those species examined, *Lotus pedunculatus*, French serradella, 'Russell' lupin, tagasaste, Caucasian clover (Black *et al.* 2014) and subterranean clover have shown promising tolerance to soil acidity and high Al levels. Since this work, Lincoln university researchers have been investigating several of these species in field experiments (see Black *et al.* 2016; Hendrie *et al.* 2018).

Low soil pH/high soil Al not only physically damages legume roots in the field, but also dramatically reduces the activity and ability of rhizobia to inoculate lucerne roots. A body of field work has been undertaken by Berenji *et al*. (2015, 2017, 2018). These workers had particular focus on 'Russell' lupin and lucerne. A key finding of this work has been that lucerne has poor N fixation capabilities under these condition, and becomes severely nitrogen (N) deficient leading to plant death.

Whitley (2018) presents new findings including defining exact soil pH/Al effects on a range of legumes and observing legume root effects of soil Al. A body of research on soil acidity and Al issues in high and hill-country soils has recently been conducted by Whitley (2018) and Whitley *et al.* 2018, ranging from soil Al on national and catchment scales, to plant rhizosphere scale. Further, the differences in soil Al for different soil orders have been reported, and the variation in soil Al within the South Canterbury catchment, providing an advanced platform of knowledge for further research.

Hendrie *et al.* (2018) presents results from a 3-year legume field trial in Omarama, that tests new deep placement lime "ripping" technology developed at Lincoln University. The soil ripper has been developed to place lime pellets up to 30 cm deep in the soil, with the aim of combating subsoil acidity. At the Omarama site the effectiveness of deep-placed lime was poor due to low annual rainfall and limited wetting of the subsoil. Hendrie has completed several experiments on Al in high-country soil, the results from which will be presented and published over the next year.

Recommendations

From a science and farm management perspective, a summary of practical recommendations is as follows:

- Soil Al (and associated low pH) is currently a critical issue in high and hill-country, and soil testing is a key tool to monitor and manage this issue
- Liming is the critical tool to ameliorate soil Al and pH issues
- Soil test Al levels of 2-3 mg/kg and above is an issue for most pasture and forage legumes, if it occurs anywhere in the plant root zone
- If lucerne is being considered, deep soil Al and pH samples should be taken, and results interpreted by an expert
- Some specialised legumes are somewhat Al tolerant. These include 'Russell' lupins and Caucasian clover.

Research gaps and future work

Overall, this body of work from Lincoln Unversity represent a starting point to improve the understanding of soil acidity and Al toxicity, and to provide management technologies to overcome what has become a serious issue in pastoral farming in New Zealand. Much more information is still required to make progress in the understanding of soil Al and toxicity. For example, why do different soils vary in exchangeable Al, and the ability to grow legumes? How does soil Al levels change within key agricultural catchments in New Zealand, and why? Is the current soil exchangeable Al test 'fit for purpose', and if not, why not? There is a need to find and test legumes which can survive and perform in high soil Al environments, and to better understand the mechanisms by which they can survive. A better understanding of how Al tolerant plants function, may allow for manipulation of these mechanisms for on-farm gains.

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