Soil pH and exchangeable aluminium in contrasting New Zealand high and hill country soils

A.E.WHITLEY[1], J.L. MOIR[1], P.C. ALMOND[1] and D.J. MOOT[2]
[1] *Department of Soil and Physical Sciences*
[2] *Department of Agricultural Sciences*
Lincoln University, PO Box 85084, Lincoln Canterbury, New Zealand
amy.whitley@lincolnuni.ac.nz

Abstract

Soil acidity and associated aluminium (Al) toxicity severely limit the establishment and growth of legumes in New Zealand high country pastures. A survey of 13 soils differing in location, soil order, parent material and climate, showed soil pH to range from 4.9 to 6.4 and exchangeable Al (0.02M $CaCl_2$) concentrations of <0.5 to 23.3 mg/kg. At all sites and at varying soil pH and profile depths, Al was present at concentrations above the toxicity threshold for sensitive legumes. Brown soils had the overall highest Al concentrations from 0.8 to 23.3 mg/kg, and volcanic soils the lowest from <0.5 to 6.7 mg/kg. The soil and environmental factors other than soil pH that drive variability in soil exchangeable Al require further investigation.

Keywords: soil pH, soil exchangeable aluminium, toxicity, soil type

Key messages

- The concentration of soil exchangeable Al, which can be toxic to legumes, was measured at 13 sites, at different profile depths and soil pH values
- Al toxicity extended across many soil orders and climatic zones in New Zealand
- Brown soils showed the highest Al concentrations from 0.8 to 23.3 mg/kg, while the volcanic soils overall had much lower Al from <0.5 to 6.7 mg/kg.

Introduction

The New Zealand high and hill country environment is often characterised by temperature extremes, a short growing season and seasonal moisture deficits (Scott *et al.* 1985). These climatic limitations coupled with acidic and often low fertility soils (N, P and S) can limit the establishment and growth of legumes (Haynes & Williams 1993).

Furthermore, soil aluminium (Al) toxicity occurs on many NZ high and hill country farms. Al availability is affected by soil pH but the relationship is poorly understood across soil orders. Higher concentrations of exchangeable soil Al (Al^{3+}) can damage plant roots, and reduce pasture growth (Scott *et al.* 2008). In particular, Al toxicity affects legumes, which supply N and provide high quality feed for stock.

The threshold concentration of exchangeable Al for sensitive pasture legumes has been stated as 3 mg/kg (0.02M $CaCl_2$), above which toxicity may occur (Moir *et al.* 2016). Al^{3+} has been suggested as the most plant-toxic Al form, with other forms being less toxic (Manoharan *et al.* 1996). However, the sensitivity of legumes to Al is variable and species specific. To mitigate Al toxicity, we need to understand which soils are most susceptible and what factors, other than soil pH, are involved. Therefore, the objective of this study was to measure the soil pH and exchangeable Al down the soil profile at different sites in New Zealand. This paper represents preliminary data contributing to a larger scale dataset.

Methods

Field soil sampling was conducted at sites with known acidity and Al issues to determine the pH and exchangeable Al concentrations of different soils across New Zealand. The locations included Canterbury, Central Otago, Marlborough, Gisborne, Waikato and Taupo. Sites varied in seasonal/annual climate (NIWA Core funded project Climate Present and Past CAOA1501), soil type, parent material and elevation (Table 1) and had a history of minimal lime inputs since land development. Soil pits were dug at all sites, profiles described and samples taken at 10 cm depth increments to 1 m or to gravel. The samples were analysed for pH (H_2O) (1:2.5 soil: water ratio) (Blakemore *et al.* 1987) and exchangeable Al, using the 0.02M $CaCl_2$ extraction method, and quantified using inductively coupled plasma atomic emission spectroscopy (ICP-OES: Varian 720-ES ICP-OES; Varian Inc., Victoria, Australia) analysis.

Soil order was derived from the New Zealand Soil Classification (Hewitt 1992).

Results

Soil Al and pH

Soil exchangeable Al ranged from <0.5 mg/kg to 22.1 mg/kg and pH varied from 4.9 to 6.4 (Table 2). The highest exchangeable Al was measured in a Brown soil from Hawea (GF). This soil is highly acidic (pH

4.9 to 5.2) throughout the profile, with a mean Al concentration that peaked at 22.1 mg/kg in the top 10 cm (pH of 4.9). Exchangeable Al was consistently high throughout the profile. The Brown soil at Tekapo (GM) also had high concentrations of Al, which also peaked in the top 10 cm of the soil at 12.4 mg/kg (pH of 5.0). A recent soil at Omarama (OM) contained Al at 13.0 mg/kg in the top 10 cm (pH of 5.3).

Many sites had lower concentrations of Al at the soil surface, but exhibited acidity and associated higher Al concentrations with increasing depth. These included soils from Gisborne (PK), Waikato (WT) and Canterbury (CA). The lowest Al value measured was <0.5 mg/kg for a Taupo pumice (AR) at 40-50 cm in the soil profile and a soil pH of 6.4. However, concentrations above 3 mg/kg were observed shallower in that profile.

Relationship between soil pH and exchangeable aluminium

Exchangeable Al and soil pH varied among soils and geographical location. The soil pH/Al relationship for the 116 samples (from the 13 sites at different depths) showed a moderate (R^2=0.65) exponential decay across the pH range of 4.9 to 6.4 (Figure 1).

Soil exchangeable Al varied significantly at any

Table 1 Site information for the 13 sites sampled across New Zealand.

Site	Location	Mean Annual rainfall (mm)	Soil order	Parent material	Elevation (m a.s.l)
AR	Taupo	1000-1300	Pumice	Pumice (rhyolitic)	495
PK	Gisborne	1600-2000	Pumice	Pumice (rhyolitic)	495
WT	Waikato	1000-2000	Allophanic	Ash (andesitic)	84
MO	Marlborough	1000-1300	Brown	Sedimentary (colluvium)	914
GM	Tekapo	800-850	Brown	Sedimentary (moraine)	765
OM	Omarama	500-600	Recent	Sedimentary (alluvial)	489
BD	Omarama	1000-1200	Brown	Sedimentary (alluvial)	545
LP	Tarras	700-800	Pallic	Sedimentary (loess)	530
GF	Hawea	600-800	Brown	Sedimentary	786
MG	Hawea	600-800	Brown	Sedimentary	564
CA	Canterbury	800-1000	Brown	Sedimentary (outwash surface)	701
EM	Canterbury	1000-1200	Brown	Sedimentary (moraine)	717
HE	Canterbury	1200-1400	Brown	Sedimentary (moraine)	735

Table 2 Exchangeable Al and soil pH at different depths in the soil profiles of 13 NZ high and hill country soils.

Site	0-10 cm		10-20 cm		20-30 cm		30-40 cm		40-50 cm	
	pH (H_2O)	Exch Al (mg/kg)	pH (H_2O)	Exch Al (mg/kg)	pH (H_2O)	Exch Al (mg/kg)	pH (H_2O)	Exch Al (mg/kg)	pH (H_2O)	Exch Al (mg/kg)
AR	5.8	2.5	5.8	3.3	6.2	1.1	6.2	0.5	6.4	<0.5
PK	5.6	1.7	5.7	4.5	5.8	5.8	5.9	4.5	5.9	2.7
WT	5.7	2.4	5.7	4.8	5.9	1.3	5.9	0.7	5.9	<0.5
MO	5.4	6.6	5.5	6.1	5.6	4.1	5.7	3.2	5.7	2.6
GM	5.0	12.4	5.4	6.3	5.1	11.7	-	-	-	-
OM	5.3	13.0	5.1	11.8	-	-	-	-	-	-
BD	5.8	1.8	5.5	6.1	5.7	7.1	5.5	9.8	-	-
LP	5.6	1.5	5.6	2.1	5.5	3.1	5.5	6.5	5.4	7.9
GF	4.9	22.1	4.9	21.3	5.2	13.7	-	-	-	-
MG	5.2	5.1	5.4	3.0	5.4	1.5	5.6	2.5	5.4	3.3
CA	5.4	5.1	5.1	18.3	5.2	17.5	5.3	16.0	5.4	15.5
EM	5.5	6.8	5.5	6.5	5.6	2.8	5.8	1.5	5.8	1.8
HE	5.3	6.8	5.3	9.5	5.5	6.9	5.5	5.9	5.4	6.2

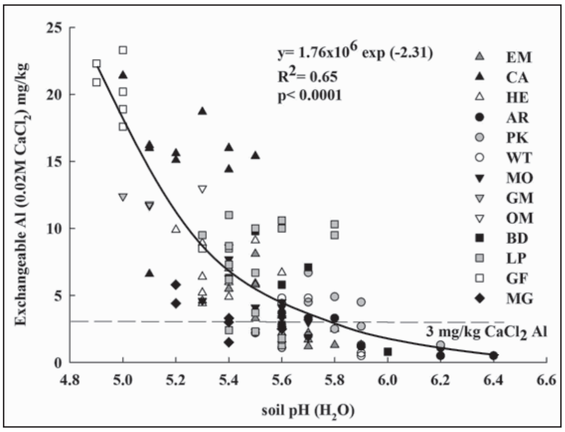

Figure 1 The relationship between soil pH (H_2O) and exchangeable Al (0.02M $CaCl_2$ extractable) for 116 soil samples from 13 sites across New Zealand. (Refer to Table 1 for soil codes).

single pH value. Individual samples had exchangeable Al concentrations above the threshold value of 3 mg/kg at pH values as high as 5.9 and could be below the threshold for pH values as low as 5.4.

Of the 13 sites sampled, Figure 1 shows that a Hawea (GF) and Canterbury (CA) site (Brown soils) had the highest concentrations of Al (>15 mg/kg) in acidic pH conditions. The sites with the lowest Al were typically North Island sites with higher pH zones in the soil profile and included pumice and allophanic soils.

Discussion

Aluminium toxicity was widespread across the sample area. Soil concentrations of Al above the toxicity threshold (3 mg/kg) for sensitive legumes (Wheeler *et al*. 1992; Moir *et al.* 2016) were measured at all sites. The depth and soil pH at which Al peaked varied between soils. For several soils, high Al was measured in the top 20 cm of the soil profile (pasture root zone) while at other sites it was measured at depths >20 cm. The depth at which Al is toxic is important in terms of selection of a suitable legume and for determining the most effective remediation. Large variability was shown in the exchangeable Al concentrations measured at a single pH, which supports the results of Moir & Moot (2014) and extends the data to include new information about other soil orders. The soil and environmental factors which drive this variability require further analysis.

In general terms, exchangeable Al concentration declined with increasing soil pH (Figure 1). The literature suggests for soils with a pH below 5.5, Al toxicity poses an issue (Bishop & Quin 2013). However, data presented here shows that soils with a pH (H_2O) of up to 5.9 may have Al concentrations that would be toxic to legumes (Figure 1). For example, the Gisborne pumice (PK) soil at a pH of 5.9 has an Al concentration of 4.5 mg/kg at 30-40 cm depth. Singleton *et al.* (1987) found similar results on a Ruawaro clay loam (pumiceous alluvium) and a Kauwhata clay loam (volcanic ash). They found an increase in Al concentration correlated with soil acidity, but also that at pH values of 6 to 7, particularly in the 0-20 cm depth, the 0.02M $CaCl_2$ Al concentration was higher than the 3 mg/kg threshold level. These authors found that no site factors could explain the high Al in the topsoil. Figure 1 shows that the soil pH (H_2O) explained 65% of the variability in exchangeable Al. The remaining variability could be due to other soil or environmental factors, such as organic matter, clay mineralogy and properties that affect the buffering capacity of the soil and the mobility of Al (McCauley *et al.* 2003).

There was no relationship between soil Al concentrations and mean annual rainfall (MAR). The MAR range across the sites was 500-2000 mm, from Omarama (OM) to Gisborne to the Waikato (PK, WT) and all soils had Al concentrations above the toxicity threshold. The two Hawea brown soils (GF and MG) had the same parent material and experience the same mean MAR and yet the GF site was much more acidic and showed much higher (more toxic) concentrations of Al compared with the MG site. This result could be related to the fertiliser history of the site, particularly application of lime. A lack of an effect of rainfall on exchangeable Al contrasts with the results of Webb *et al* (1986), who found that the leaching of bases, acidity and exchangeable Al increased markedly with rainfall and the degree of development of moraine soils near Lake Pukaki. However, their study isolated the variability in Al along a rainfall gradient (same parent material) compared with this study, which covered a larger area and a range of soil parent materials. Harrison *et al.* (1990) studied two chronosequences under different rainfall on moraine and terrace soils near Craigieburn, Canterbury. They showed higher exchangeable Al in moraine soils, on mountain slopes with high rainfall, compared to the terrace soils.

This field soil survey clearly shows soil order is an important factor contributing to the variability in exchangeable Al. Soil order relates to the degree of development of a soil, parent material and climatic conditions (Hewitt 1992). Data presented in this paper show that, overall, the brown soils (GF, MO, MG, GM, CA, EM and HE sites) had higher concentrations of Al than the pallic, recent and volcanic soils. Brown soils form under higher rainfall, are older and have undergone weathering and acidification. Pallic soils occur under lower rainfall and recent soils are much younger than brown soils, which results in reduced weathering and acidification which in turn contributes to lower Al concentrations. Lower concentrations of Al were found in the volcanic soils (pumice and allophanic) compared with many of the South Island soils formed from greywacke. However, there was still Al present at concentrations above 3 mg/kg in the volcanic soils. The overall lower Al present in the volcanic soils is an interesting result and currently unexplained. These data indicated that high Al concentrations followed the sequence of Brown>Pallic≥Recent>Allophanic≥Pumice. However, this study had limited sample numbers and therefore more extensive data analyses are currently underway to confirm this result. These findings support other work conducted by Hochman *et al* (1992) showing high Al concentrations in New Zealand brown soils.

This field survey involved the collection of soil profile samples at 13 sites in New Zealand to determine the pH and exchangeable Al concentrations. The next phase will use legumes as bio-indicators to determine if the soil Al toxicity measure ($CaCl_2$ extraction) equates to plant growth.

ACKNOWLEDGEMENTS

Ballance Agri-Nutrients Ltd provided funding for this research. Sephrah Rayner, Lyn Carmichael, and Natasha Barbier assisted in fieldwork in association with Landcare Research. Landcorp farms Ltd, Peter Jordan, the farmers and Duncan Clarke.

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