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ASSESSING THE SIGNIFICANCE OF CADMIUM IN NEW ZEALAND AGRICULTURAL SYSTEMS – PRELIMINARY RESULTS

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Introduction

The New Zealand economy relies heavily on the primary production sector and the use of phosphate fertilisers. Cadmium (Cd) occurs naturally in the phosphate rock used to produce phosphate fertilisers and is present in fertiliser at varying levels. Cd may be taken up into plants and thereby into people and livestock. Plant uptake from soil is the key factor affecting food chain transfer. The plant uptake of Cd is influenced by a number of factors including crop species and cultivars (e.g. Alexander et al. 2006; Cheng et al. 2008). Furthermore, soil properties including soil pH, organic matter (OM), salinity, cation-exchange capacity, clay content, and availability of macronutrients, and micronutrients such as Zn, have all been recognised to influence Cd uptake in plants (Grant et al. 1998; Chaney 2012). Relationships between soil properties and plant uptake are often used as the basis for setting soil guideline values to ensure protection of human health from consumption of home-grown produce and to ensure food standards are met (Cavanagh 2013, De Vries and McLaughlin 2013). Amending soil properties provides a means to reduce plant uptake of Cd, as does the use of low Cd-accumulating cultivars (e.g. Grant et al 2007).

Wheat, potatoes, onions and leafy green vegetables are key crops to provide a perspective on the significance of Cd in New Zealand agricultural soils. Bread and potatoes are the main sources of dietary Cd (Vannoort & Thomson 2011), which in turn is the dominant source of Cd in the non-smoking population (FAO/WHO 2010). Potatoes and onions are the highest value vegetable exports in New Zealand, valued at around $105M and $97M respectively in 2014 (Plant and Food Research 2014). Finally, leafy green vegetables are considered to be higher accumulators of Cd , relative to root and tuber vegetables or fruit (e.g. Alexander et al. 2006), and in this respect can provide a sensitive indicator of plant uptake of Cd from New Zealand agricultural soils.

Pastoral land is the dominant agricultural land use in New Zealand and has been shown to have elevated concentrations of Cd in some regions (Cavanagh 2014). Ryegrass/clover systems are the dominant pasture species, although increasingly additional species, such as the herbs chicory and plantain, or forage crops, such as kale, fodder beet and maize, are used to improve the resilience of the pastoral system (e.g. coping with moisture stress, or to provide higher quality feed over winter). Grazing animals take up Cd mainly via consumption of herbage (Lee et al. 1996; Loganathan et al. 1999), which may lead to food standards being exceeded in kidneys sold as offal (Roberts et al. 1994).

Rhizobia are a group of bacteria that are important symbionts of pasture legumes such as clovers. The symbiosis results in formation of specialised 'root nodules', containing a mixture of legume host tissue and rhizobia bacteroid cells, which function together to fix atmospheric nitrogen (N_2) into plant available forms. Through grazing and deposition, this symbiosis effectively supplies 'free' nitrogen to the pastoral sward, maintains soil fertility, and reduces the need for mineral fertiliser N to support pasture growth.

Previous reports have shown that N-fixation by *Rhizobium leguminosarum*, the species most commonly associated with pasture legumes (i.e. white clover) is sensitive to Cd (Broos et al. 2004). Furthermore, rhizobia-legume symbiosis (nodulation index) has been proposed as an indicator for assessing adverse effects on soil organisms in heavy metal (including Cd) contaminated soils (Manier et al. 2009). However, most studies have been focused on heavily contaminated sites, where Cd has accumulated from industry, mining, or application of sewage sludge to land. The effects of relatively lower levels of Cd contamination on rhizobia and the rhizobia:legume symbiosis in agricultural soils is not well understood.

This preliminary assessment of the significance of soil Cd concentrations in New Zealand agriculture measured the uptake of Cd in economically important cultivars of wheat, potatoes, onions and leafy green vegetables and important pasture and forage crops, and assessed Cd effects on soil rhizobia.

Methods

- Composite soil and plant samples were collected from existing industry trials and/or commercial fields (Figure 1) and analysed for Cd and other analytes.

  For food crops, the plant uptake factor (PUF) was used to measure plant uptake (i.e. phytoavailability) of Cd in different soils:

  $$PUF = \frac{Cd_{plant}\ (mg/kg\ (DW))}{Cd_{soil}\ (mg/kg\ )}$$

  This equation can be rearranged to estimate the nominal soil concentration at which the food standard may be reached ($Cd_{soillimit}$), and the increase in current soil Cd concentrations that may lead to non-compliance with food standards (Cd accumulation risk).

- Soils from Pukekohe and Levin were used for a series of experiments to assess the efficacy of organic amendments to the soil to reduce plant uptake of Cd, and the longevity of this effect.
- The effects of soil Cd on rhizobia was assessed through field surveys and isolation of rhizobia from pasture soils to assess rhizobia tolerance and Cd toxicity to clover and Rhizobia.

Figure 1. The crops and number of cultivars (in brackets) sampled at each location.

Results

Food crops:

Cadmium concentrations in specific crops typically varied with cultivar (Figures 2, 3) and location (Figure 3,4). The relative Cd uptake by different cultivars was often not consistent at different locations (e.g. RV1 in Figure 3).

Soil Cd concentrations did not necessarily reflect plant Cd concentrations which is demonstrated by the differences in the calculated plant uptake factors and Cd accumulation risk for each location (Table 1, Figure 5).

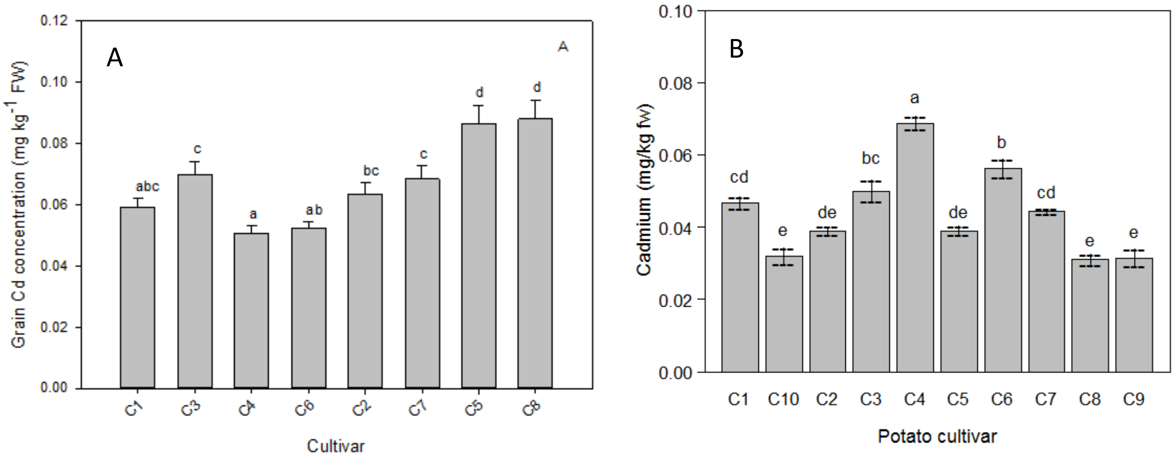

Figure 2. Cadmium concentrations (mg kg FW^{-1}) in A) wheat grain from cultivars grown at Methven (n = 4) and B) peeled potato tubers of cultivars grown at Lincoln (n=3). Mean and standard error labelled with the same letter are not significantly different (P < 0.05).

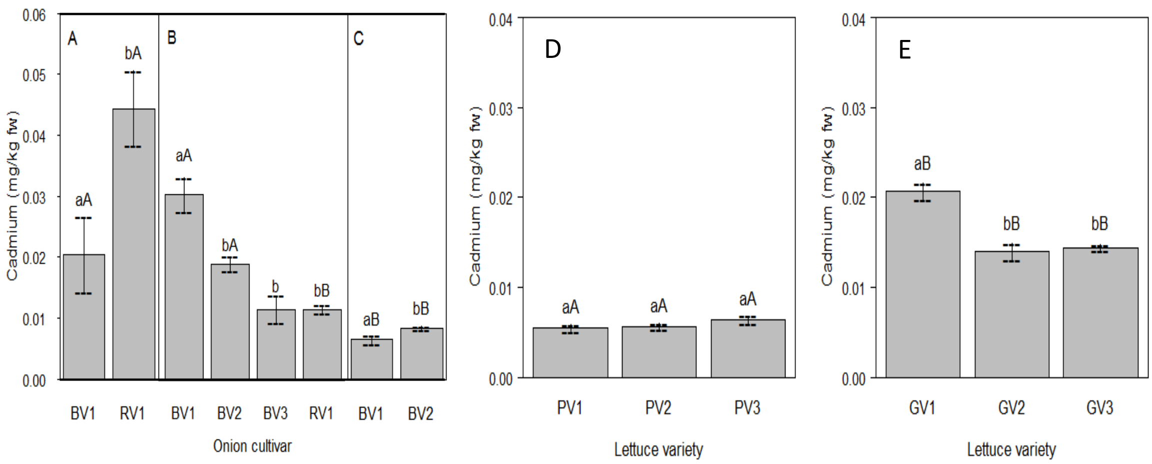

Figure 3. Cadmium concentration in onion cultivars (mg/kg FW) from A) Pukekohe, B) Waikato and C) Rakaia in three iceberg lettuce varieties (mg/kg (FW)) from D) Pukekohe (P) and E) Gisborne (G). Mean (n = 4) and standard error indicated by the same lower case letter are not significantly different (*P* < 0.05) *within* a given site (lower case letters) or *between* sites (capital letters).

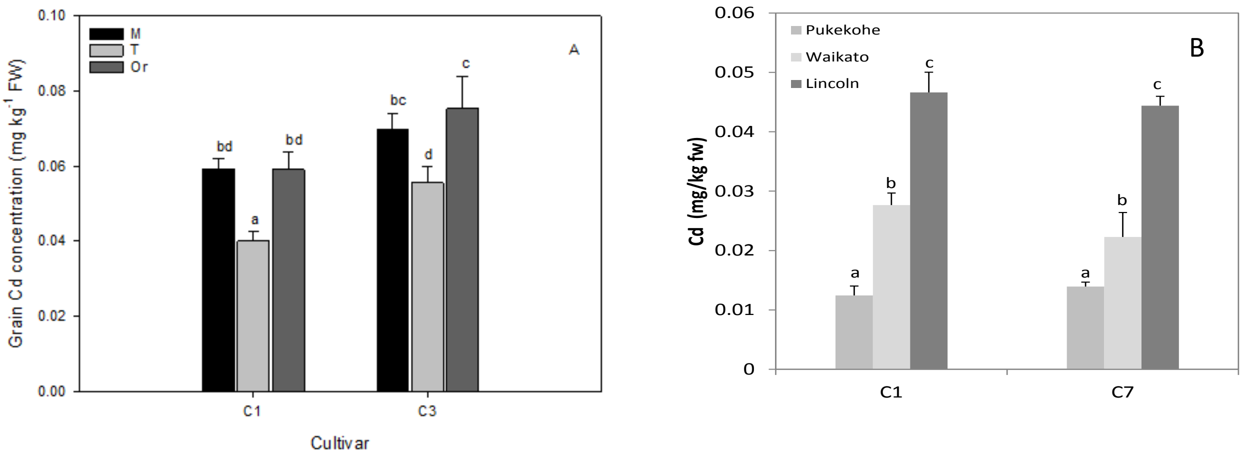

Figure 4. Mean cadmium (Cd) concentrations (mg/kg (FW)) in A) grain from C1 and C3 cultivars grown at Methven (M), Temuka (T) and Oreti (Or) sites (n = 4) and B) tubers from C1 and C7 potato cultivars grown at Pukekohe, Waikato and Lincoln (n=3). Mean and standard error labelled with the same letter are not significantly different (*P* < 0.05).

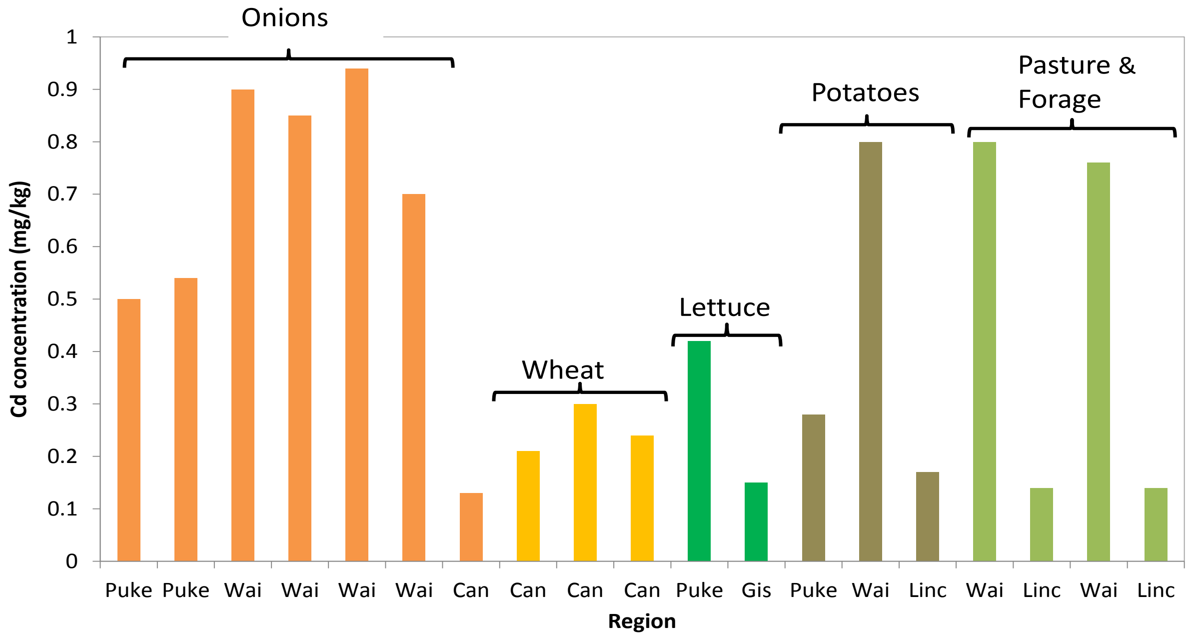

Figure 5. Soil Cd concentrations (mg/kg) in transect samples from each sampling location. Puke-Pukekohe, Wai – Waikato, Can – Canterbury, Gis – Gisborne, Linc-Lincoln.

Table 1. Generalised plant uptake factors (PUF) and Cd accumulation risk for different regions and crops.

Region	PUF	Cd accumulation risk[1]
Pukekohe (lettuce, onion, potato)	<0.5[2]	>4-fold
Lincoln (potatoes, pasture, forage crops)	0.5–1 (potatoes) >1 (chicory, plantain, fodder beet)	2-4-fold (potatoes)
Methven	<0.5 (wheat)	<2-fold (wheat)
Rakaia (onions)	<0.5	>4-fold (onion)
Temuka (wheat)	<0.5	2-4-fold (wheat)
Oreti (wheat)	<0.5	<2-fold
Gisborne (lettuce)	>1	>4-fold
Waikato (potatoes, onions, pasture, forage crops)	<0.5[2] 0.5–1 (fodder beet)	>4-fold

[1] The increase in current soil Cd concentrations at the PUF determined for the relevant crop and location, which could lead to food standards being exceeded. Not assessed for pasture or forage crops. [2]One site/crop combination had high uptake.

Mitigation of cadmium uptake

The addition of lime and different organic materials reduced the uptake of Cd into potato tubers (Figure 6). Other experiments showed that organic amendments reduced plant uptake and the chemical measures of phytoavailability of Cd for over a year.

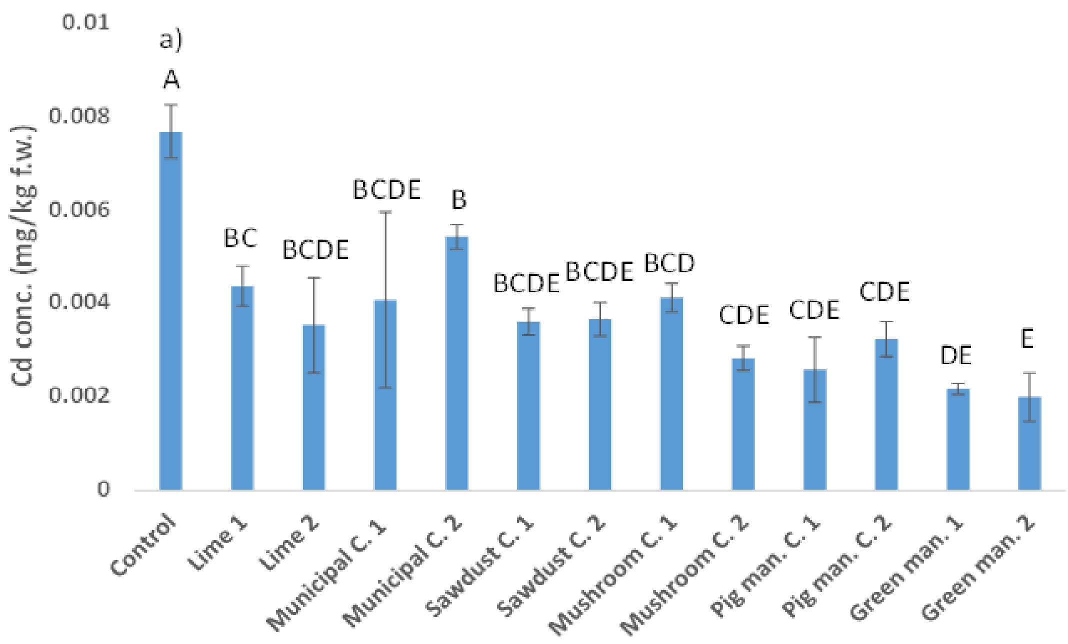

Figure 6. Cadmium (Cd) concentration (mg/kg (FW)) in potato tubers. Mean (n=3) and SE of the mean labelled with the same letter are not significantly different (P>0.05).

Pasture and forage crops

Chicory and plantain had higher Cd concentrations than other pasture species (Figure 7). The significantly different chicory Cd concentration at two sites in Waikato is suggested to be due to differences in soil pH (data not shown).

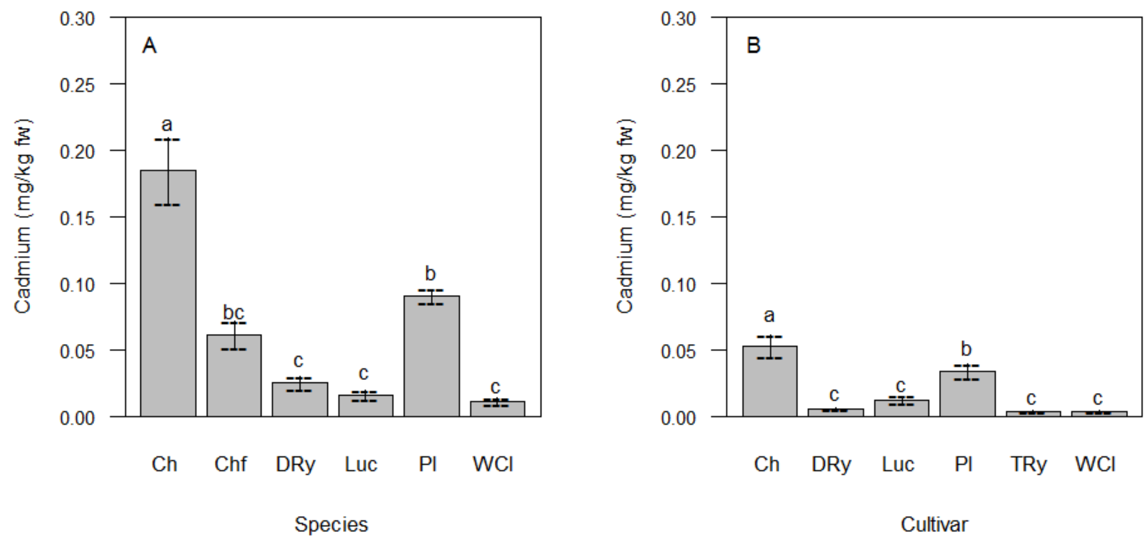

Figure 7. Cadmium concentration (mg/kg (FW)) in pasture varieties from A) Waikato (n=3) and B) Lincoln (n=4). Ch -chicory, Chf - chicory from the forage site, Luc - lucerne, Pl - plantain, WCl - white clover, DRy – diploid ryegrass, TRy - tetroid ryegrass. Cadmium concentrations labelled with different letters are significantly different (*P*<0.05).

Leaf Cd concentrations of all forage crops were higher than other plant components, with kale having the lowest Cd concentrations (Figure 8).

Figure 8. Cadmium (Cd) concentration (mg/kg (FW)) in different forage crops from A) Waikato and B) Lincoln. No detectable Cd concentrations were found in maize cobs.

At high concentrations Cd had negative effects on the growth (as measured by respiration) of rhizobia isolated from pasture soils and grown under laboratory conditions (i.e. in Cd-containing solution), with the current commercial strain, TA1, being most sensitive (Figure 9). Conversely, the toxicity of Cd to clover appears to be moderated by *R. leguminosarum* TA1 (data not shown). Further details on the rhizobia testing are available from Wakelin et al (2016).

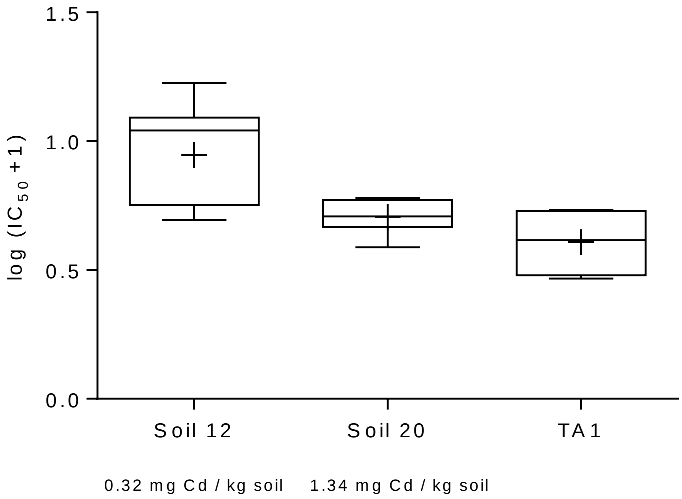

Figure 9. Toxicity of Cd to the growth (respiration) of rhizobia strains isolated from soil 12 (Whataroa), soil 20 (Morrinsville) and the commercial inoculant strain, TA1. Whiskers extend from the minimum to maximum values, while the box extends from the 25th to 75th percentiles, with median show as a line in the box and mean shown as a +.

Discussion and conclusions:

Species, cultivar and soil properties (in particular pH and organic matter) influence the extent to which Cd can be taken up by different agricultural crops in New Zealand soils. In general, food and forage crops and pasture met relevant food or animal feed standards, although the mean concentrations in some cultivars of potato, wheat and onions at specific sites are approaching maximum limits. In pot trials, spinach and silverbeet showed the potential to accumulate high concentrations of Cd from soil used for commercial growing of leafy green vegetables (data not shown). However, it should be noted that pot trials can overestimate Cd uptake relative to field conditions. The plant uptake of Cd from different soils varied, with soils from Gisborne and Lincoln typically showing higher uptake, while soils from Pukekohe and Waikato typically showing lower uptake. Soils with a high plant uptake require more active management to ensure food standards are met, although fortunately, many locations with a high plant uptake have low soil Cd concentrations. Increases of between 1.3 and 14 times the current soil Cd concentrations were estimated to potentially result in the exceedance of food standards by individual crops in different locations; wheat is identified as the crop most at risk of exceeding food standards with minimal increases in soil Cd concentrations.

There was variation in Cd uptake by different cultivars of wheat, onions, potato and lettuce, although, the relative order of Cd uptake by individual cultivars was often not consistent between different sites. This suggests an interaction of Cd uptake by individual cultivars with soil properties. Nonetheless, three cultivars of wheat were identified as being low Cd-accumulating cultivars, two wheat cultivars as being high-Cd accumulating cultivars and one potato cultivars also identified as a low Cd-accumulator. Some cultivars were only assessed at one location, hence further verification of the relative order of Cd uptake is required to confirm Cd-accumulating status at different locations. The inclusion of Cd uptake as an assessment parameter in plant breeding trials would provide a cost-effective means of identifying high and low Cd-accumulating cultivars.

In general, pasture and forage crop Cd concentrations were low; however, some species (chicory and plantain) demonstrated the potential for high accumulation of Cd. The significance of these higher concentrations is unknown. Using New Zealand-specific data on the ingestion of different feeds with existing models on Cd uptake in livestock would provide an initial assessment of the significance of the Cd concentrations in pasture and forage crops, and specifically whether exceedance of food standards (e.g. in offal) or toxicity concerns may arise. Research on Cd uptake by chicory and plantain is the focus of another study (e.g. Stafford et al 2016); this will provide a more comprehensive assessment of the factors influencing Cd uptake in these species.

While the influence of soil properties on Cd uptake was not the primary focus of this study, some insights were gained. Soil pH most often appears to be a dominant influence on Cd uptake, with organic matter content also important. These findings confirm earlier observations of their significance in agricultural crops in New Zealand (Roberts et al. 1995; Gray et al. 1999a,b,c) and from the international literature. Manipulation of these soil properties (e.g. amending soil with lime and compost) at sites observed to have a high plant uptake would enable the significance of those properties on Cd uptake for a given crop to be determined, as well as assessing the efficacy of those measures to reduce plant uptake in the field. In the current study, compost addition to soil was demonstrated to reduce uptake of Cd of potatoes in pot trials, and to also reduce phytoavailable Cd for over a year.

Cadmium, at high concentrations and under laboratory conditions, was demonstrated to have negative effects on the growth of rhizobia isolated from New Zealand pastures, with the current commercial strain, TA1 being most sensitive. Conversely, the toxicity of Cd to clover appears to be moderated by *R. leguminosarum* TA1. These effects were observed at concentrations higher than current environmental concentrations, although concentrations at which no or low effects are observed, and the effect of Cd on the rhizobia/legume symbiosis, particularly with regards to N uptake are still to be determined.

The results of the this study have been used to inform a further research program to better understand the influence of soil properties on Cd uptake in , including field trials and further investigation of the effects of Cd and some preliminary investgiations on Cd uptake in livestock.

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