Geoderma Regional 7 (2016) 11–18

Contents lists available at ScienceDirect

Geoderma Regional

journal homepage: www.elsevier.com/locate/geodrs

Cadmium accumulation by forage species used in New Zealand livestock grazing systems

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ARTICLE INFO

Article history:
Received 26 August 2015
Received in revised form 11 November 2015
Accepted 19 November 2015
Available online 2 December 2015

Keywords:
Cadmium
Accumulation
Forage
Livestock
Superphosphate

ABSTRACT

Cadmium (Cd) accumulation in 12 forage plant species was investigated in a glasshouse trial. Potted soil (total Cd 0.43 mg kg^{-1}) was fertilised with varying rates of superphosphate to manipulate phosphorus availability, plant growth rate and soil Cd availability. Mean tissue Cd concentration decreased in the order chicory > plantain > turnip > lucerne > sheep's burnet > strawberry clover > kale > perennial ryegrass > haresfoot trefoil > red clover > crimson clover > white clover. Chicory and plantain had significantly greater mean tissue Cd concentrations (1.639 and 0.734 mg kg^{-1} DM, respectively) than all other species. Rate of superphosphate and plant yield had little influence on plant tissue Cd concentration. The correlation between soil total Cd and plant tissue Cd concentration was generally poor ($R^2 = 0.006–0.428$) and was only significant for perennial ryegrass and red clover. Modelling of lamb kidney Cd accumulation indicated that food standard maximum levels may be exceeded in animals younger than the current meat industry 30 month offal discard age. With increased use of chicory and plantain as specialist forage crops in New Zealand, this information will be important for improving livestock Cd accumulation risk assessment models.

1. Introduction

New Zealand is heavily dependent on revenue generated from ruminant grazing systems, with dairy, meat and edible offal accounting for approximately 40% of total export earnings (Treasury, 2015). To sustain intensive pasture production from New Zealand's naturally low phosphorus (P) status soils regular P-fertiliser application is necessary (McLaren and Cameron, 1996). Historically phosphate rocks used for local superphosphate manufacture were rich in Cd (Loganathan et al., 2003). Cadmium accumulation in New Zealand agricultural soils is strongly correlated to P-fertiliser application history (Bramley, 1990; Roberts et al., 1994).

Although the native Cd concentrations in New Zealand agricultural soils are similar to concentrations found worldwide (Roberts et al., 1994; McDowell et al., 2013) ongoing soil Cd accumulation is undesirable. This is because plants have little ability to regulate Cd uptake; and, as a consequence, plant tissue Cd concentration increases with increasing soil Cd concentration (Adriano, 1986; Smolders and Mertens, 2012). Left unmanaged, Cd accumulation in agricultural soils has potential to increase Cd concentration in food products, thereby increasing human dietary Cd intake.

In 2011, a Tiered Fertiliser Management System (TFMS) was introduced to manage on-going soil Cd accumulation in New Zealand agricultural land (MAF, 2011). Within the TFMS, five soil Cd management tiers are defined based on four soil total Cd trigger concentrations; 0.6, 1.0, 1.4 and 1.8 mg kg^{-1} soil dry weight (Cavanagh, 2012). The basic premise of the TFMS is that as soil Cd tier-status increases, increasing restrictions apply to P-fertiliser type and/or rate of application, so as to manage further Cd inputs and minimise on-going soil Cd accumulation. Beyond the uppermost trigger value of 1.8 mg kg^{-1}, no further soil Cd accumulation is permitted, without a site-specific risk investigation being undertaken (Warne, 2011). Although the TFMS provides a suitable basis for managing soil Cd accumulation, it is not designed to specifically manage risks arising from plant Cd accumulation in agricultural systems. This is because soil Cd phytoavailability is influenced by a range of soil factors (McBride et al., 1997; Gray et al., 1999c, b; Li et al., 2003), and because plant Cd accumulation is both species and cultivar specific (Florijn and Van Beusichem, 1993; Gray et al., 1999a; Gray et al., 2001; Gray and McLaren, 2005; Smolders and Mertens, 2012).

Ruminant-grazed pastoral systems represent the predominant agricultural land use in New Zealand, accounting for approximately 12 million hectares (StatsNZ, 2013). Although more than 99% of dietary Cd is excreted (Van Bruwaene et al., 1984; Lee et al., 1994; Lee et al., 1996) Cd is known to accumulate in the liver and kidney of livestock due to high levels of metallothionein synthesis in these tissues (Lee et al., 1994; Lee et al., 1996). Because of the efficiency of these organs at sorbing and storing metals, Cd is not expressed in significant quantities in either meat or milk products (Solly et al., 1981; Sharma et al., 1982; Morrison, 1988).

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http://dx.doi.org/10.1016/j.geodrs.2015.11.003

To minimise the risk of food standard Cd maximum level (ML) exceedances in livestock liver and kidney tissue, the New Zealand meat industry currently discards ruminant liver and kidney from trade for human consumption for animals older than 30 months (MAF, 2008). However, exceedances in animals younger than 30 months were first predicted by the modelling of Loganathan et al. (1999), with increased liver and kidney Cd accumulation being linked to increased dietary Cd exposure (Lee et al., 1994; Lee et al., 1996).

Soil ingestion (estimated for sheep at 0.06–0.1 kg day^{-1} (Healy, 1967; Rodrigues et al., 2012) and dairy cows at 0.25–1.24 kg day^{-1} (Healy, 1968; Rodrigues et al., 2012)) can contribute to total livestock dietary Cd intake; however, the majority (approximately 90%) occurs via the forage they consume (Lee et al., 1996; Roberts and Longhurst, 2002). Because of this, grazing stock on Cd-rich forages may result in more rapid kidney/liver Cd accumulation, potentially leading to more frequent exceedance of food standard MLs.

While substantial research into plant Cd uptake and accumulation was undertaken during the 1990s, the majority of historic research on animal forages has been focussed on ryegrass and clover species (Table 1). The common theme of literature is that Cd concentrations in ryegrass–white clover pastures are relatively low, with concentrations typically being greater for ryegrass than white clover (Roberts et al., 1994; Loganathan et al., 1997; Gray et al., 1999a, b). Roberts et al. (1994) reported that the Cd concentration in unspecified pasture weed species was significantly greater than both grass and clover species. Parker et al. (2008) reported Cd concentrations of a plantain/chicory/red clover/white clover forage stand to be approximately 4–5 times greater than an adjacent ryegrass–white clover pasture; however species-specific data was again not presented and soil Cd data was not included.

Since the 1990s, there has been significant diversification in New Zealand farms systems with the integration of a variety of new forage species for which there is little documented information on Cd uptake and accumulation. For example, summer- and winter-grazed forage brassicas are integral in providing a reserve of high quality feed for livestock when pasture growth rate and/or quality is poor. Furthermore, chicory and plantain are increasingly being sown as monoculture stands or in combination with red or white clover, due to their high feed quality, growth rate and persistence over the hot, dry summer period, which traditional ryegrass–white clover pastures struggle to tolerate. Developing Cd accumulation data for key forage species used in modern farm systems is therefore desirable to improve sensitivity and accuracy of animal Cd accumulation models (Reiser et al., 2014) and to ensure that appropriate Cd management strategies are developed and implemented on-farm. The study described in this paper was carried out with the purpose of initiating this data collection.

2. Methodology

A glasshouse pot trial was designed to test the relative potential for twelve forage species to take up and accumulate P and Cd in their above ground vegetative tissue (data on P uptake and accumulation are presented in McDowell and Cosgrove (2015)). Soil was collected from the A horizon (10–15 cm depth) of a commercial dairy farm in the district of Hillend, near Balclutha in South Otago (Table 2). After collection, the soil was air dried and sieved (<2 mm) before being transferred into pots.

Two different pot sizes were used in this trial. 15 cm diameter pots containing 2.5 kg of air-dried soil were used for ryegrass, legume and herbaceous species and an unplanted 'fallow' treatment (plant species 1–10; Table 3). Larger pots (22 cm diameter) containing 4 kg of air-dried soil were used for the two brassica species (plant species 11 & 12; Table 3).

Lime (laboratory grade $CaCO_3$) was mixed into each pot at 1400 mg kg^{-1} (approximately equivalent to 2000 kg ha^{-1}) with the purpose of increasing soil pH to within the agronomic optimum range of 5.8–6.0. Calcium sulphate and potassium chloride were mixed into the soil (both at 500 mg kg^{-1}) prior to planting.

2.1. P-fertiliser treatments

To modify soil P and Cd availability, superphosphate (9.5% Total-P, 9.0% P soluble in 2% citric acid, and 168 mg Cd kg^{-1} P) was ground and mixed into the potted soil. In addition to a control (zero P-fertiliser), plant species 1–10 and an unplanted fallow treatment received superphosphate at 200, 400, 600, 800 and 1000 mg kg^{-1} soil (equivalent to 19, 38, 57, 76 and 95 mg P kg^{-1} soil, and 0.0032, 0.0064, 0.0096, 0.0128 and 0.0160 mg Cd kg^{-1} soil, respectively) while plant species 11 & 12 were limited to two superphosphate rates; 600 and 1400 mg kg^{-1} soil (equivalent to 57 and 133 mg P kg^{-1} soil, and 0.0096 and 0.0233 mg Cd kg^{-1} soil, respectively). Following fertiliser mixing, the soil was watered to near field capacity using deionised

Table 1
Summary of Cd accumulation data for various forage species in New Zealand.

Reference	Type of study	Findings
Crush and Evans (1990)	Glasshouse trial	Pot trial investigating effect of soil pH on herbage element concentrations in chicory. Mean Cd concentration of 3 mg kg^{-1} DM that was not affected by change in soil pH.
Roberts et al. (1994)	Field survey	For fertilised pastoral sites, mean tissue Cd concentration descended in the order: weeds (0.28 mg kg^{-1} DM) > grasses (0.10 mg kg^{-1} DM) > legumes (0.06 mg kg^{-1} DM). Plantain noted as a key weed species, but no species-specific data presented.
Loganathan et al. (1995)	Field survey	Fertilised low slope areas dominated by ryegrass/white clover, with pasture Cd concentration ranging between ~0.05–0.22 mg kg^{-1} DM
Lee et al. (1996)	Field trial	Fertilised ryegrass/white clover dominant pasture with plant tissue Cd concentrations ranging between 0.12–0.3 mg kg^{-1} DM.
Loganathan et al. (1997)	Field trial	Cd concentration in grass and clover pasture components in a long-term fertiliser trial ranged between 0.025–0.225 mg kg^{-1} DM and ~0.01–0.08 mg kg^{-1} DM, respectively.
Gray et al. (1999a)	Glasshouse trial	Mean Cd concentration in white clover ~0.1 mg kg^{-1} DM (range 0.023–0.427 mg kg^{-1}DM), perennial ryegrass ~0.15 mg kg^{-1} DM (range 0.066–0.3 mg kg^{-1} DM) and lucerne ~0.45 mg kg^{-1} DM (range 0.074–1.428 mg kg^{-1} DM)
Gray et al. (1999b)	Glasshouse trial	Mean Cd concentration in white clover 0.2 mg kg^{-1} DM (range ~ 0.1–0.9 mg kg^{-1}DM) and perennial ryegrass 0.3 mg kg^{-1} DM (range ~ 0.1–0.6 mg kg^{-1} DM).
Roberts and Longhurst (2002)	Field survey	Fertilised easy slopes and stock camps dominated by ryegrass/white clover, with pasture Cd concentration ranging between ~0.1–0.3 mg kg^{-1} DM.
Parker et al. (2008)	Field trial	Cd concentration was around 4–5 times higher in a plantain/chicory/red clover/white clover forage stand (0.36–0.75 mg kg^{-1} DM) than in a corresponding ryegrass/white clover pasture (0.11–0.22 mg kg^{-1} DM). No species-specific data presented.
Reiser et al. (2014)	Field survey	Survey of dairy/intensive cattle pastures revealed 90% of ryegrass dominant pastures had Cd concentrations less than 0.2 mg kg^{-1} DM, with a mean of 0.13 mg kg^{-1} DM.