



Municipal composts reduce the transfer of Cd from soil to vegetables[☆]



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ARTICLE INFO

Article history:

Received 4 October 2015

Received in revised form

21 January 2016

Accepted 25 January 2016

Available online xxx

Keywords:

Biowastes

Lignite

Soil amendments

Heavy metals

Trace elements

ABSTRACT

Cadmium (Cd) is a non-essential trace element that accumulates in agricultural soils through the application of Cd-rich phosphate fertiliser. Vegetables can accumulate Cd to concentrations that sometimes exceed food safety standards. We investigated the potential of low-cost soil amendments to reduce Cd uptake by spinach (*Spinacia oleracea* L.), lettuce (*Lactuca sativa* L.) and onion (*Allium cepa* L.). Batch sorption experiments revealed the relative sorption of Cd by biosolids, charcoal, lignite, sawdust, two types of compost, bentonite and zeolite. Lignite and compost had the greatest ability to sorb Cd and were subsequently selected for pot trials, which elucidated their effect on Cd uptake by onions, spinach and lettuce in two market garden soils with native Cd concentrations of 1.45 mg/kg and 0.47 mg/kg. The addition of 2.5% (dry w/w) municipal compost reduced the Cd concentration in onions, spinach and lettuce by up to 60% in both soils. The addition of lignite gave variable results, which depended on the soil type and rate of addition. This Cd immobilisation was offset by soil acidification caused by the lignite. The results indicate that municipal compost is a low-cost soil conditioner that is effective in reducing plant Cd uptake.

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1. Introduction

Cadmium (Cd) is a non-essential element that can cause many negative health effects at high concentrations (Kabata-Pendias and Mukherjee, 2007). It occurs naturally as a contaminant in all phosphate rocks, although the concentrations vary considerably, depending on the origin of the parent material. Rock phosphate originating from igneous rock generally has Cd concentrations of 0.7–30 mg/kg P (Oosterhuis et al., 2000), whereas rock phosphate refined from sedimentary rocks may contain Cd concentrations higher than 556 mg/kg P (Mar and Okazaki, 2012). Rock phosphate from sedimentary rock sources account for some 85–90% of world P production (Oosterhuis et al., 2000). Phosphate fertiliser use has resulted an enrichment of Cd in agricultural soils worldwide (Kabata-Pendias and Mukherjee, 2007; Hooda, 2010). Historically, New Zealand and Australia manufactured superphosphate using phosphate rock from Nauru and Christmas Island, which contained

relatively high Cd concentrations >600 mg Cd/kg P (Syers et al., 1986). Repeated application of this Cd-rich superphosphate for most of the 20th century has resulted the significant increases in the Cd concentrations in NZ soils (Taylor, 1997).

The transfer of Cd from soil to plants and thence into food products is well documented (Alloway et al., 1990; McLaughlin et al., 1998; Berkelaar and Hale, 2003; Lopez-Chuken and Young, 2010; Arcella et al., 2012). Enriched soil Cd concentrations cause increased Cd accumulation in crops (Nan et al., 2002; Kabata-Pendias and Mukherjee, 2007). Cadmium accumulation varies between plant species, varieties and cultivars (Crews and Davies, 1985; McLaughlin et al., 1994a; Kabata-Pendias and Mukherjee, 2007; Grant et al., 2008; Gartler et al., 2013). Different parts of the plant have distinct cadmium concentrations. For example, vegetable species such as spinach (*Spinacia oleracea* L.) and lettuce (*Lactuca sativa* L.), accumulate higher concentrations of Cd in the edible portions than perennial ryegrass (*Lolium perenne* L.) (Gartler et al., 2013). An increase in soil pH decreases plant Cd-uptake (Kabata-Pendias and Mukherjee, 2007). Although Zn can have both synergistic and antagonistic effects on plant Cd-uptake (Grant et al., 1999), Cd is often a food-chain toxicity risk in Zn deficient

[☆] This paper has been recommended for acceptance by Wen-Xiong Wang.

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agricultural systems (Hooda, 2010). Soil Cl increases the mobility of Cd in soil resulting elevated Cd concentrations in plants (McLaughlin et al., 1994b).

In New Zealand (NZ), these concerns led to the formation of the Cadmium Working Group (CWG)-established by the NZ government in 2006. The CWG identified vegetable production as being the industry most at risk from superphosphate-derived Cd (Cadmium Working Group, 2008). The fertilizer industry, in collaboration with regulators has developed a Tiered Fertilizer Management System (TFMS) (Rys, 2011). Here, soils with <0.6 mg/kg Cd have no restriction placed on the application of P fertilizers. Soils with concentrations >0.6 and < 1.0 are permitted restricted use of P fertilizers to ensure that the soil does not exceed 1.8 mg/kg Cd after 100 years. Intensive monitoring and modelling is required for soils with Cd concentrations >1.4 and < 1.8 mg/kg. No further Cd accumulation is permitted in soils with Cd concentrations >1.8 mg/kg (Rys, 2011).

Plants in soil take up Cd from the soil pore water. While most of the Cd in soils is usually associated with soil colloids (>98%), with only a small fraction of the total is available for plant uptake in soil solution (Christensen and Haug, 1999). By manipulating the amounts of available cation binding sites in soils, the amount of dissolved Cd can be reduced, resulting in a subsequent reduction in uptake by plants (Kabata-Pendias and Mukherjee, 2007). This can be achieved by a number of different methods, such as changing the soil pH (e.g. by liming) or by introducing additional binding sites. For example, Fe and Mn oxides sorb Cd (Zasoski and Burau, 1988; Backes et al., 1995) and can be used to reduce the movement of Cd in soil solution. Humic substances, produced during the decomposition process of organic materials, include a large group of amorphous, colloidal organic polymers (McLaren and Cameron, 1996). These molecules carry a predominantly negative charge arising from ionizable carboxyl and phenolic hydroxyl functional groups, which enable humic substances to act as a cation exchanger in soil and thus remove metal cations from solution (McLaren and Cameron, 1996). Specific sorption also plays an important role (Pentari et al., 2009). As Cd is a chalcophilic trace element, it is expected to bind relatively strongly to organic sulphur groups (Kabata-Pendias and Mukherjee, 2007), R-SH, R-S-R, R-SS-R and heterocyclic S, which might be present in organic matter (e.g. lignite) (Calkins, 1994).

Various organic and inorganic amendments are used in agricultural lands for improving the physical and chemical conditions of soil (Sarwar et al., 2008). Moreover, both organic (e.g. sawdust, peat, compost, etc.) and inorganic (e.g. lime) soil amendments can effectively reduce Cd solubility and plant uptake in highly contaminated soils (Bolan et al., 2003; Guo et al., 2006). Lignite (added at a rate of 1%) reduced the solubility of Cd and decreased the transfer of Cd from soil to *Lolium perenne* (L.) by 30%, while not detrimentally affecting soil fertility (Simmler et al., 2013).

To date, most studies investigating the use of lignite or compost to reduce the plant uptake of Cd have considered highly contaminated soils (Ciecko et al., 2001; Skłodowski et al., 2006; Pusz, 2007; Tapia et al., 2010) that are not representative of most agricultural soils where Cd concentrations typically reach a few mg/kg at most (Alloway and Steinnes, 1999). Other studies that investigated the fate of Cd in compost-amended land focused on the endogenous Cd in the compost itself (Rutzke et al., 1993; Chang et al., 1997; Hanc et al., 2009), which may be contaminated through industrial emissions into wastewater treatment plants.

We aimed to investigate potential soil amendments that could reduce the transfer of Cd from soils to plants in two different NZ market garden soils with elevated Cd concentrations. To achieve these aims, we used batch sorption experiments to identify promising amendments and then used selected amendments in

targeted pot trials to assess the efficacy of these amendments to reduce Cd uptake by vegetables.

2. Materials and methods

2.1. Soil sample collection

Soils were collected from two commercial vegetable growing areas in Pukekohe (37°13'18.92"S 174°52'5.94"E) and Levin (40°38'17.49"S 175°14'23.61"E) in the North Island of NZ. Soil from the top 0.25 m were collected and large stones and roots removed manually. The soils were dried, ground, passed through a 7 mm sieve, and homogenised. Three 500 g sub samples of each soil were collected which were then ground and sieved through a 2 mm Nylon mesh. Tables 1A and 1B shows the chemical and physical properties of the soils. Both soils had elevated total Cd concentrations (1.45 mg/kg and 0.47 mg/kg respectively).

2.2. Soil amendment collection

Eight materials were considered as potential soil amendments for reducing the phytoavailability of Cd in soils. These were: commercially available bentonite, which is an aluminium phyllosilicate, essentially impure clay consisting mostly montmorillonite (Theng, 2012), zeolite powder which is a microporous aluminosilicate mineral commonly used as commercial adsorbent; charcoal; lignite; sawdust; biosolids and two types of compost. Zeolite powder and bentonite were provided by Commodities NZ Ltd., Wellington. Charcoal was produced by Solid Energy New Zealand Ltd. Biosolids were collected from Kaikora sewage waste treatment plant, NZ. Solid Energy New Zealand Ltd. provided the lignite in powdered form; it originated from the New Vale open cast mine in Southland, NZ. Living Earth compost (municipal compost) was collected from Living Earth Ltd. (Christchurch branch, NZ) and Parkhouse compost was collected from Parkhouse Garden Supplies (Christchurch, New Zealand) outlets. Living Earth compost is produced from municipal green waste including lawn clippings, tree prunings, and food waste, while Parkhouse compost is made from sawdust composted and animal residues (manure and carcasses). The sawdust was collected from a local sawmill (Shands Road Saw mill Ltd., Rolleston, Christchurch, NZ) produced from *Pinus radiata*. After collection, samples were dried, ground and passed through a 2 mm Nylon sieve. Tables 1A and 1B shows the chemical and physical properties of the materials.

2.3. Sample analysis

The pH values of the sieved samples were determined using a (Mettler Toledo pH meter in high purity water (18.2 MΩ resistivity; Heal Force® SMART Series, SPW Ultra-pure Water system, Model-PWUV) at a solid/water ratio of 1:2.5 (1:10 for composts, charcoals and lignite). The mixtures were left to equilibrate for 24 h before measurement (Blakemore, 1987).

The Cation Exchange Capacity (CEC) of the materials was measured using the 0.01 M Silver Thiourea (AgTU) method (Blakemore, 1987). Briefly, 35 mL of 0.01 M AgTU was added to 0.70 g of dry sample in a 50 mL centrifuge tube and then agitated in an end-over-end shaker for 16 h. Samples were centrifuged at 2000 rpm for 10 min. The supernatant was filtered through a Whatman no. 40 filter and analysed using an Inductively Coupled Plasma-Optical Emission Spectrometer (ICP-OES) (Varian 720 ES - USA). The total carbon and nitrogen were analysed in soil and compost samples using an Elementar Vario-Max CN Elementar analyser (Elementar®, Germany).

For both plants and soils, pseudo-total elemental analyses were

Table 1A
Properties and macronutrient concentrations of the materials used in the experiments.

Properties	Lignite	Living Earth compost	Parkhouse compost	Sawdust	Charcoal	Biosolids	Zeolite powder	Bentonite	Pukekohe soil	Levin soil
pH	4.6	7.4	7.0	4.8	6.7	3.6	5.9	8.8	6.0	6.5
CEC (me/100 g)	45	45 (0)	47 (0)	9.3 (0)	3.3 (0)	11 (1)	21 (0)	44 (0)	22*	15*
C (%)	59 (1)	21	21	48	40	26 (0)	<0.02	0.7	2.1*	1.2*
N (%)	0.83 (0.00)	2.3	1.6	0.1	0.13	2.6 (0.03)	0.03	<0.02	0.23*	0.13
P	201 (1.7)	4178 (37)	5159 (227)	23 (1)	118 (10)	3805 (66)	<1	124 (9)	3414 (26)	2247 (20)
S	4942 (94)	2644 (27)	3610 (70)	49 (10)	58 (2)	6395 (201)	<1	768 (16)	491 (6)	296 (1)
Ca	14,216 (314)	24,903 (588)	37,416 (1456)	556 (16)	1505 (39)	4967 (66)	12,084 (89)	17,131 (306)	4147 (117)	7008 (99)
Mg	2496 (40)	4177 (16)	2186 (34)	158 (5)	458 (21)	2305(31)	3663 (29)	6838 (189)	2400 (95)	2873 (43)
K	200 (6)	14,938 (33)	5412 (67)	425 (1)	975 (25)	1564 (16)	10,506 (46)	1621 (265)	1951 (59)	2242 (54)

Values are in mg/kg unless otherwise indicated. Standard errors are given in brackets (n = 3). * Data from Hill Laboratories, NZ.

Table 1B
Trace element concentrations (mg/kg) of the materials used in the experiments.

Properties	Lignite	Living earth compost	Parkhouse compost	Sawdust	Charcoal	Biosolids	Zeolite powder	Bentonite	Pukekohe soil	Levin soil
B	36 (0)	20*	<1	5.9 (0.1)	<1	14 (0)	<1	17 (1)	33 (0)	9 (0)
Cd	0.31 (0.15)	0.70 (0.10)	0.45 (0.10)	0.03 (0.01)	0.05 (0.03)	1.6 (0.05)	<0.01	0.93 (0.29)	1.5 (0.03)	0.47 (0.01)
Cu	2.8 (0.2)	59 (1)	25 (1)	37 (3)	2.4 (0.2)	555 (15)	1.9 (0.0)	25 (1)	65 (1)	20 (0.2)
Zn	4.3 (0.5)	310 (11)	34 (2)	5.3 (0.3)	16 (2)	912 (16)	34 (2)	72 (2)	173 (1)	67 (1)
Cr	2.1 (0.1)	28 (1)	37 (1)	63 (5)	0.74 (0.04)	33 (1)	0.71 (0.1)	4.2 (0.1)	40 (2)	15 (0.3)
Ni	3.7 (0.3)	9.3 (1)	5.2 (0.1)	<1	0.42 (0.1)	18 (0.5)	<1	1.9 (0.1)	25 (1)	7.4 (0.5)
Pb	3.5 (1)	123 (3)	4.5 (1)	<1	<1	101 (1)	4.5 (1)	5.9 (0.3)	55 (0.5)	7.4 (0.1)

Standard errors are given in brackets (n = 3). * data from Hill Laboratories, NZ.

carried out using microwave digestion in 8 mL of Aristar™ nitric acid ($\pm 69\%$), diluted with milliQ water to a volume of 25 mL and filtered using Whatman no. 52 filter paper (pore size 7 μm). The concentrations of Cd together with other elements (Ca, Mg, K, P, S, B, Cu, Zn, Cr, Ni and Pb) were determined using inductively coupled plasma optical emission spectrometry (ICP-OES Varian 720 ES – USA) in soils (Kovács et al., 2000) and in plants (Gray et al., 1999a). Reference soil and plant material (International Soil analytical Exchange – ISE 921 and International Plant analytical Exchange IPE 100) from Wageningen University, the Netherlands, were analysed for quality assurance. Recoverable concentrations were 91%–108% of the certified values.

An estimation of the phytoavailable fraction of Cd in the soils and soil amendments was determined using 0.05 M $\text{Ca}(\text{NO}_3)_2$ extraction (Gray et al., 1999b; Black et al., 2012). Significant correlations between concentrations of Cd in extractions that simulate soil solutions and plant (cereals, pasture and several vegetable species) Cd have been reported (Gray et al., 1999b; Black et al., 2012), in both spiked and unspiked soils. Briefly, 5 g of soil was mixed with 30 mL of extractant in a centrifuge tube and a suspension was formed using a vortex mixer. The centrifuge tube was then agitated on an end-over-end shaker for 2 h after which it was centrifuged at 3000 rpm for 15 min. After filtering (Whatman no. 52 filter paper), the samples were analysed to determine the concentration of Cd and other elements using inductively coupled plasma optical emission spectrometry (ICP-OES Varian 720 ES – USA) in soils. Five blank samples were also run along with samples during the analysis following all steps.

2.4. Batch sorption experiment

The batch sorption experiment was conducted with eight soil amendments and two soils, at four different pHs (six for lignite) ranging from 3.4 to 7.5 and six Cd concentrations. Each treatment was replicated three times. Following the method of Simmler et al. (2013), we prepared spiked solutions in 0.05 M $\text{Ca}(\text{NO}_3)_2$ solution using $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ (BDH AnalaR). We added $\text{CdSO}_4 \cdot 8\text{H}_2\text{O}$ (BDH AnalaR) in 0.05 M $\text{Ca}(\text{NO}_3)_2$ solution to achieve Cd concentrations

of 0, 1.4, 6.8, 13.2, 18.9 and 24.5 mg/L in 0.05 M $\text{Ca}(\text{NO}_3)_2$ solution. Five grams of soil or amendment was mixed with 30 ml of each of the spike and control (0 mg Cd/L) solutions. The pH was adjusted close to the target pH using HNO_3 (made from BDH ARISTAR nitric acid 70%) or 2 M KOH (BDH AnalaR KOH) to decrease or increase pH, respectively. Pilot studies were carried out with each material following the batch sorption experiment steps and by adding different amount of HNO_3 or KOH solution to determine how much of HNO_3 or KOH solution would be needed to get a desired pH.

The mixture was agitated using a vortex mixer for 3 min, shaken on an end-over-end shaker for 2 h, and centrifuged at 10,000 rpm for 10 min. The supernatant was filtered through a Whatman no. 52 filter paper in to 30 mL vials and were analysed using Flame Emission Atomic Absorption Spectrophotometer (AAS). A parallel ICP-OES analysis was carried out on randomly selected samples from the bulk samples to confirm the results of the AAS. The monitoring validated the Flame Emission Atomic Absorption Spectrophotometer's performance in detecting low concentrations of Cd after Cd sorption by different soil amendments.

The Cd adsorption coefficient (K_d) for the different soil amendments were determined according to the following equation (Simmler et al., 2013)

$$K_d = \frac{\text{Cd sorbed by the soil or soil amendments} \left(\frac{\text{mg}}{\text{kg}} \right)}{\text{Cd in solution} \left(\frac{\text{mg}}{\text{L}} \right)}$$

$$= \frac{(C1 - (C2 - C3)) * 0.03}{(C2 - C3) * 0.005}$$

where, K_d is the solid-solution distribution co-efficient. In the equation, C1 is the initial Cd concentration in solution (for our batch experiment they were 1.4, 6.8, 13.2, 18.9 and 24.5 mg/L), C2 is the Cd concentration in solution (mg/L) after equilibrium in a given batch (either with soil or soil amendments) with Cd spiking and C3 is the Cd solution concentration (mg/L) in the corresponding batch without Cd spiking (only with 0.05 M $\text{Ca}(\text{NO}_3)_2$ solution).

2.5. Pot trial

A pot experiment was conducted with lignite and one compost. The coarsely-sieved soils were mixed with the amendments using a concrete mixer to give the following treatments: control, 1.05% (w/w) lignite (henceforth “1% lignite”), 2.63% (w/w) lignite (henceforth “2.5% lignite”, henceforth “lignite”), and 2.7% (w/w) compost (henceforth “2.5% compost”, henceforth “compost”). The soil amendments were added on a dry weight basis. Subsamples of each soil treatment were transferred into 2.5 L pots (approx. 3 kg dry weight) into which onion (*Allium cepa* L. var. Pukekohe long keeper), spinach (*Spinacia oleracea* L.) and lettuce (*Lactuca sativa* L. var. Buttercrunch) were planted with five replicates for each treatment–vegetable combination. The pots were placed in a randomised block design in the Plant Growth Unit (greenhouse) at Lincoln University, where they were watered daily to field capacity. Before sowing, the soils, mixed with different soil amendments, were kept for two weeks in the green house and watered daily to equilibrate. The nutrient status of the pots was maintained by periodic applications of Ruakura solution (Smith et al., 1983). A total of 0.25 g N/pot, 0.04 g P/pot and 0.23 g K/pot was applied together with other micro nutrients, those are present in Ruakura solution in each pot throughout the growing period in to two split applications, one at first week and other at the 4th week.

The plants were grown for 6–10 weeks before harvest (February–April). Temperatures ranged between 9 °C and 20 °C during the nighttime (10 pm until 6 am) and between 14 °C and 28 °C during the daytime. At harvest, the edible portions of the plants were excised and the fresh weight determined. Both the edible portions and the residual material was washed thoroughly with deionised water and placed in a drying cabinet at 70 °C until a constant weight was obtained. Samples were then ground and stored in airtight containers until chemical analyses. After harvest, soil was sampled from each of the spinach treatments, ground, and sieved to <2 mm through a Nylon mesh. Soil pH and total and $\text{Ca}(\text{NO}_3)_2$ -extractable Cd concentrations were determined as described above.

The data was analysed using ANOVA with Fisher's Least-Significant-Difference post-hoc test to compare means using Minitab® 17 (Minitab Inc, State College, Pennsylvania, USA). The level of significance was 0.05.

3. Results and discussion

3.1. Batch sorption experiment

Fig. 1 shows the Cd sorption, expressed as $\log(K_d)$ (sorbed/solution concentration coefficient), by the potential soil amendments in a solution of 1.4 mg/L Cd. K_d values for the 6.8, 13.2, 18.9 and 24.5 mg/L Cd solutions were significantly lower (data not shown), indicating saturation of the binding sites on the materials tested. While a soil solution concentration of 1.4 mg/L Cd is well above concentrations found in most agricultural soils, our results indicate that the K_d values obtained were still within the linear range for the materials tested and thus can be considered analogous to lower Cd concentrations.

At controlled pH values, the two composts and lignite had the greatest capacity to bind Cd across a range of pHs (Fig. 1), which is consistent with the findings of similar batch sorption experiments (Ulmanu et al., 2003; Simmler et al., 2013). Charcoal and zeolite had low K_d values, which is consistent with the findings of Hanauer et al. (2012). Kelly et al. (2014) suggested that this may be because the charcoal sorbs more Cd in soil than in the batch experiments due to the longer contact time with the Cd in soil solution. The effectiveness of charcoal in sorbing Cd may have been

better if it were more weathered (Cui et al., 2014). Fard et al. (2011) reported that biosolids were an effective sorbent for Cd and that the K_d value for biosolids increased substantially with increasing pH. While biosolids may be an effective sorbent for highly contaminated soils, Simmler et al. (2013) reported that in agricultural soil, biosolids increased extractable Cd and increased plant Cd uptake. Our K_d values for bentonite were similar to those reported by Ulmanu et al. (2003). Sawdust, zeolite powder and charcoal had similar or only slightly higher K_d values than the Pukekohe and Levin soils. This indicates that these amendments are unlikely to provide a significant increase in Cd sorption in these soils.

The Cd K_d values of all materials increased with increasing pH (Fig. 1), consistent with other work carried out using lignite and soil (Simmler et al., 2013). The sensitivity of K_d to pH differed between materials. The binding of Cd by lignite was more sensitive to pH than the composts, with the composts sorbing more Cd at lower pH values.

We chose the Living Earth compost and lignite for the pot trial because the batch experiment revealed that they had high K_d values over a range of solution pHs. Living Earth compost was selected over Parkhouse compost because of its lower cost (NZ\$12/tonne c.f. NZ\$100/tonne).

3.2. Plant uptake of cadmium

On a fresh weight basis, spinach grown in the Levin soil accumulated the highest shoot Cd concentration (0.10 mg/kg FW, Fig. 2), similar to the World Health Organisation's and Food Standards of Australia and New Zealand's limit for Cd in vegetables of 0.1 mg/kg (Bigdeli and Seilsepour, 2008; FSANZ, 2015) and lower than the CODEX limit of 0.5 mg/kg FW (Chaney et al., 2009). This soil contained just 0.49 mg/kg Cd (Table 1B), less than the lowest tier on the TFMS (Rys, 2011). The Cd concentrations in the shoots of lettuce grown on the same soil were significantly lower, as were the Cd concentrations in spinach and lettuce grown on the Pukekohe soil. The Cd concentrations in the onions growing in both soils were significantly lower than the Cd concentrations found in spinach or lettuce. This is consistent with other findings (Gartler et al., 2013) that also showed high Cd uptake by shoot material of a variety of commercially grown vegetables, including lettuce and spinach. Moreover, genetic variations between cultivars can result in significant differences in Cd uptake (Crews and Davies, 1985; McLaughlin et al., 1994a; Kabata-Pendias and Mukherjee, 2007; Grant et al., 2008).

The 0.05 M $\text{Ca}(\text{NO}_3)_2$ -extractable Cd concentrations in the two soils reflected the concentrations of Cd in the shoots of the lettuces grown in those soils. However, the concentrations of Cd in the shoots of spinach grown on the two soils do not reflect either the total or the extractable Cd concentrations in those soils (Table 1A and 1B). The higher Cd accumulation by vegetables grown in Levin soils compared to Pukekohe soils may be partially due to the lower Zn concentrations in the Levin Soils. Many authors reported that increased soil Zn concentrations could reduce Cd accumulation by plants (McKenna et al., 1992; Grant et al., 1999; Kabata-Pendias and Mukherjee, 2007; Chaney et al., 2009). Zinc also affects the transfer of Cd from plants to animals or humans. McKenna et al. (1992) reported that Cd in spinach was less bioavailable to quail than Cd in lettuce. They also report that increased Zn concentrations in lettuce and spinach Zn reduced the retention of Cd in kidney and liver.

The compost treatment decreased Cd uptake by more than 20% in onions, spinach and lettuce in both the Pukekohe and Levin soils (Fig. 3). This finding is consistent with reports of Cd decreases using other composts in highly contaminated soils (Tapia et al., 2010). This decrease is consistent with the addition of function groups that

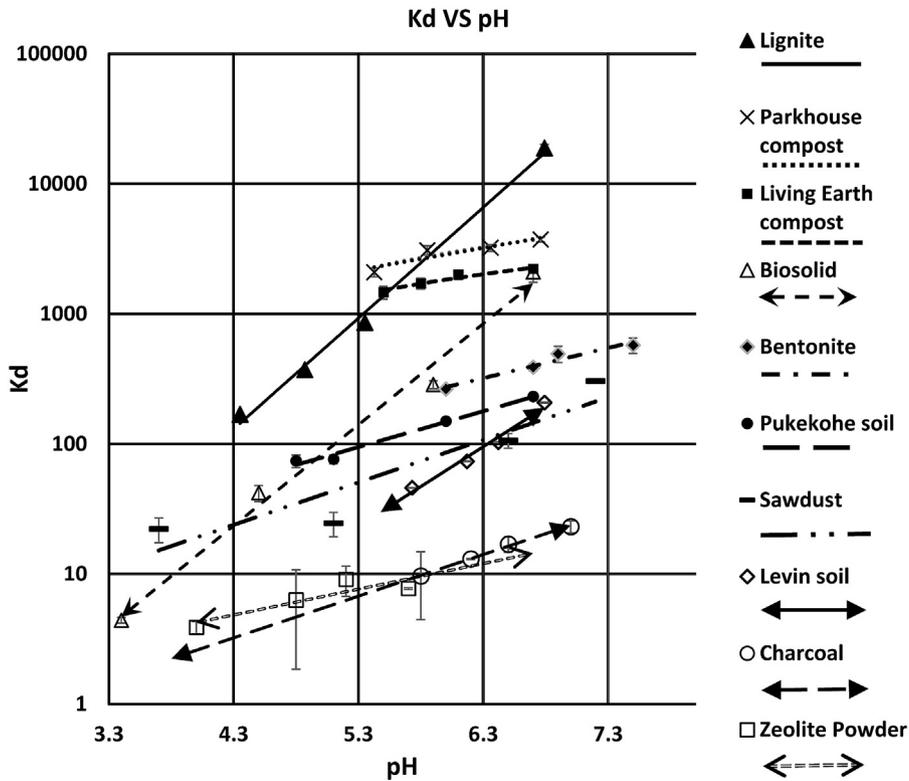


Fig. 1. The K_d values of Pukekohe and Levin soil and different soil amendments through a range of pH values. Error bars represent the standard error of the mean ($n = 3$).

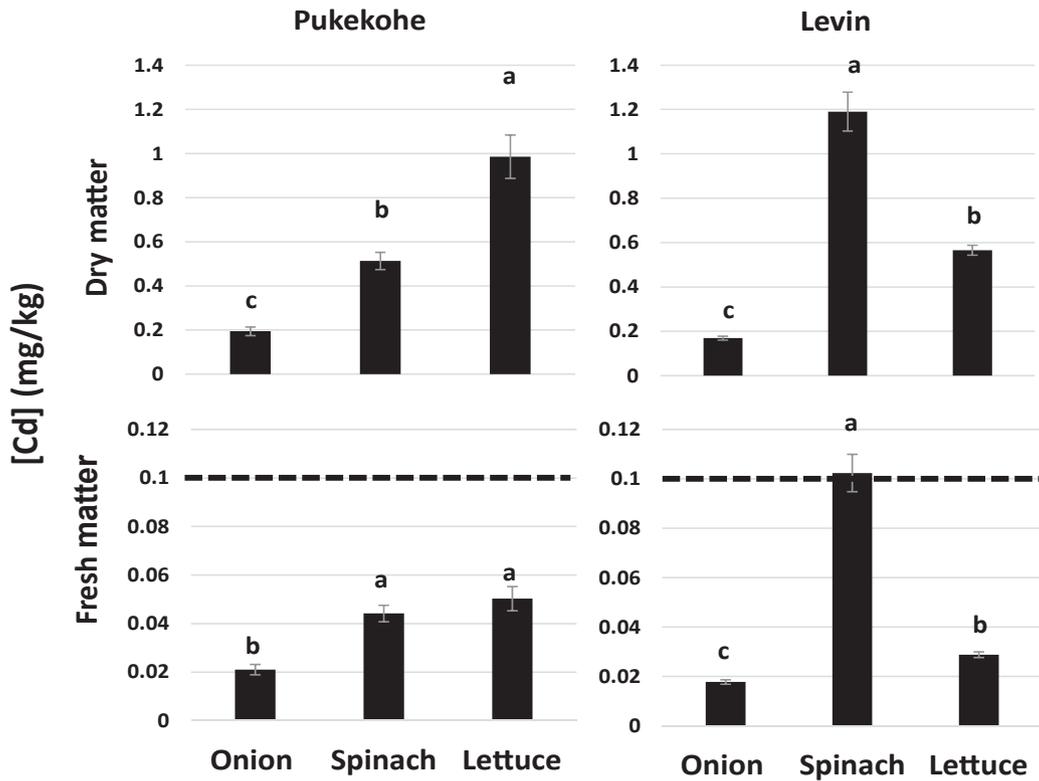


Fig. 2. Average dry matter and fresh matter Cd concentrations in the edible portions of selected vegetables grown in control soil. The dotted line illustrates the World Health Organisation's and Food Standards of Australia and New Zealand's limit for Cd in vegetables (Bigdeli and Seilsepour, 2008; FSANZ, 2015). Error bars represent the standard error of the mean ($n = 5$). Values with the same letter are not significantly different.

may bind Cd through cation exchange or specific adsorption (Simmler et al., 2013). The composts contained significant Zn concentrations (Table 1B), which may have further reduced plant uptake as described above. In the Pukekohe soil, compost addition increased the pH from 6.0 to 6.2, which would likely reduce plant Cd uptake (Kabata-Pendias and Mukherjee, 2007). The compost had no significant effect on the pH of the Levin soil.

The 2.5% lignite treatment in the Levin soil significantly reduced the Cd concentrations in the plant shoots by at least 10%. However, there were no significant differences between the Cd concentrations in onion and spinach grown in treated and control Pukekohe soils. Moreover, the 2.5% lignite treatment significantly increased the Cd concentration in the lettuce grown in the Pukekohe soil. The 1% lignite treatment of the Levin soil reduced the transfer of Cd from soil to the shoots of the vegetables by 28–34% when compared to the untreated soil (Fig. 3). A similar result was observed in the 1% lignite treated Pukekohe soil, with the exception of spinach, where no significant decrease was observed. Overall, the lower rate of lignite treatment appears to have been more effective in reducing Cd uptake by vegetables grown on these soils. In contrast, the higher rate may increase Cd uptake by lettuce. The difference between the two treatments may be due to the change in pH: the 2.5% lignite treatment decreased the pH significantly from 6.5 to 6.2 in the Levin soil and 6.0 to 5.7 in Pukekohe soil, while the pH change caused by the 1% treatment was less (0.1 pH unit decrease in both soils). As shown in the batch sorption experiment, a pH decrease may result in less Cd being bound by the lignite and the soil particles (Fig. 1).

Overall, the compost treatment was the most effective and consistent in reducing the transfer of Cd from soil to vegetables in both the soils. This may be partly due to the high CEC of the

compost, which enables Cd immobilisation through non-specific or specific adsorption retention of the Cd onto soil colloids (Kabata-Pendias and Mukherjee, 2007). However, as shown in the batch sorption experiment, the nature of the binding sites (*c.f.* inorganic: zeolite powder, bentonite; and organic: compost, biosolids) may also be important, especially under variable pH conditions.

3.3. Practical implications of lignite or compost addition

With the exception of lettuce growing in the Pukekohe soil and spinach growing in the Levin soil, the compost treatment did not significantly change the biomass of the vegetables grown in the pot trial, despite the additional nutrients provided by the compost. This is unsurprising given the high nutrient status of the soils prior to treatment (Tables 1A and 1B) and addition of nutrient solution in all pots. Importantly, none of the treatments caused a significant reduction in the biomass production of the plants in either soil (Table S1). No chlorosis or malformation of the plants was observed, which indicates that the use of these amendments are unlikely to cause fertility problems in the short-term.

Translating the rates of 1% and 2.5% into tonnes per hectare gives 33 and 81 t/ha respectively, assuming a ploughing depth of 0.25 m and a soil density of 1.3 g/cm³. The cost of adding 1% lignite @ NZ\$350 per tonne is therefore \$11,550 per hectare, which is prohibitively expensive. Compost on the other hand is more effective and the addition of 2.5% @ NZ\$12 per tonne would cost just \$975 per hectare. Moreover, the high N and P concentrations in the compost (Table 1A) could reduce fertiliser costs and also reduce further Cd increase in the soils which could be expected with injudicious applications of fertiliser derived from phosphate rock.

Living Earth compost (municipal compost) achieved significant

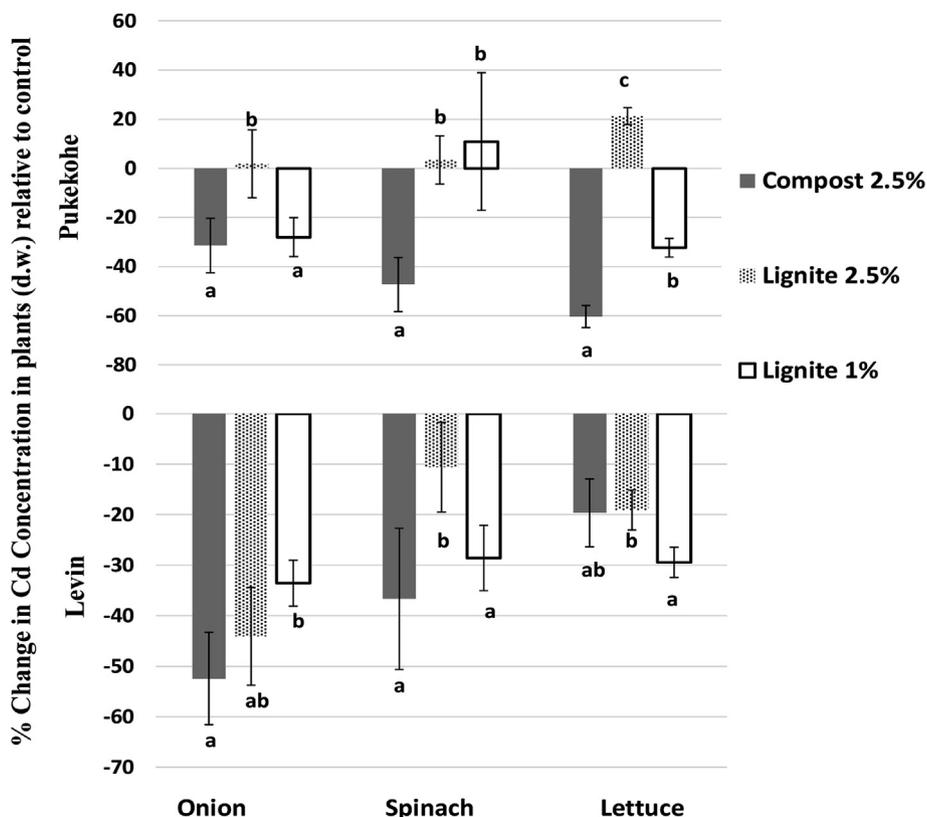


Fig. 3. Changes in Cd concentrations (dry matter) in the edible portions of selected vegetables relative to the control. Error bars represent the standard error of the mean ($n = 5$). Values for the same plant with the same letter are not significantly different.

and consistent reductions in plant shoot Cd concentrations in the three vegetables grown in the two soils without causing any reduction in plant growth or the uptake of other essential nutrients. In nutrient poor soils, compost could provide an additional source of important plant macronutrients, such as N, P and K while improving the structural properties and water retention characteristics of the soil. Reusing municipal compost reduces the expense of disposing this material into landfills. Monitoring is required to ensure that further contaminants are not added with the composts. Composts may be a low-cost means of extending the useful life of the soil before Cd concentrations proscribe food production. Composts are heterogeneous mixtures of highly variable composition. The composition of municipal compost varies seasonally and by location, and the performance of various composts in reducing plant uptake of Cd over the long-term is a fertile area for future research. Determination of the mechanisms by which composts immobilise Cd in the soil-plant system could elucidate how other composts might perform and how variability in the compost parent material might affect its ability to bind Cd.

Acknowledgements

The senior author would like to thank NZAID for a doctoral scholarship. This research was supported by the Centre For Integrated Biowaste Research (CIBR). We gratefully acknowledge the constructive and detailed comments provided by the reviewers of this manuscript.

Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.envpol.2016.01.072>.

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