Published online July 27, 2017

Effects of Lime and Organic Amendments Derived from Varied Source Materials on Cadmium Uptake by Potato

Shamim Al Mamun, Niklas J. Lehto, Jo Cavanagh, Richard McDowell, Munmun Aktar, Ebrahim Benyas, and Brett H. Robinson*

Abstract

Repeated applications of Cd-rich phosphate fertilizers have resulted in elevated concentrations of this toxic element in some New Zealand soils. Exceedance of the food safety standard for Cd (0.1 mg kg^{-1} fresh weight) has been reported for potato (*Solanum tuberosum* L.). Composts may efficiently sorb Cd in soil and therefore reduce its phytoavailability, leading to reduced uptake by plants. We aimed to determine the potential of various composts, shredded corn stover, and lime at two different rates to reduce the transfer of Cd from a soil (containing 1.45 mg kg^{-1} Cd) to potato (var. 'Nadine'). In the control, the peeled tubers, skins, leaves, and stems had Cd concentrations of 0.04, 0.09, 0.26, and 0.53 mg kg^{-1} dry weight, respectively. There was a 71% reduction in tuber Cd concentrations in potatoes grown in soil amended with 5% (w/w) shredded corn stover, although it significantly decreased potato biomass. Potatoes grown in soil amended with pig manure compost, mushroom compost, sawdust-animal waste compost, and municipal compost at rates of either 2.5 or 5% (w/w) reduced tuber Cd concentrations by 58 to 66%, 46 to 63%, 52 to 53%, and 29 to 49%, respectively. Lime (1.3%) application in soil reduced tuber Cd concentrations by 50%. Composts significantly increased tuber biomass. Further work is warranted to identify the key components of composts that result in reduced Cd uptake by plants.

Core Ideas

- Composts made from contrasting source materials reduced Cd uptake by potatoes.
- Unlike lime, composts did not result in reduced micronutrient uptake.
- Composts resulted in a greater biomass increase than lime.

J. Environ. Qual. 46:836–844 (2017)
doi:10.2134/jeq2017.02.0059

Supplemental material is available online for this article.
Received 6 Feb. 2017.
Accepted 29 May 2017.
*Corresponding author (brett.robinson@lincoln.ac.nz).

Cadmium (Cd), a nonessential trace element (Kabata-Pendias and Mukherjee, 2007), has accumulated in many soils worldwide (Hooda, 2010; Kabata-Pendias and Mukherjee, 2007; Kabata-Pendias and Pendias, 2001). Humans are exposed to Cd through contaminated food products, which may result in adverse health effects (Bernard, 2008; Dziubanek et al., 2015; Fekete et al., 2001; Järup and Åkesson, 2009; Peters et al., 2010; Sigel et al., 2013). The concentration of Cd in the renal cortex of the kidneys increases with time.

Cadmium accumulates in agricultural soils from the repeated application of phosphorus (P) fertilizers (Loganathan et al., 2003; Pérez and Anderson, 2009; Roberts et al., 1994; Schipper et al., 2011; Taylor, 1997; Taylor et al., 2007) as well as industrial activities and the land application of biosolids (Kabata-Pendias and Mukherjee, 2007). It has been reported that Cd may be accumulating in New Zealand soils (N. Kim, unpublished data, 2005), with market garden soils accumulating more than other agricultural practices because of higher fertilizer inputs (Cadmium Working Group, 2011). Cadmium in agricultural land is of concern in New Zealand and Australia because these countries historically manufactured superphosphate using phosphate rock from Nauru and Christmas Island containing relatively high Cd concentrations (>600 mg Cd kg^{-1} P) (Syers et al., 1986).

Increased Cd in soil has been linked to increased uptake by plants (Dziubanek et al., 2015; Fekete et al., 2001; Krauss and Diez, 1997; MacLean, 1976; McLaughlin et al., 1997; Pérez and Anderson, 2009; Rai et al., 2015; Weggler-Beaton et al., 2000) and accumulation in the food chain (EFSA, 2012; N. Kim, unpublished data, 2005).

Potatoes (*Solanum tuberosum* L.) are a staple food in many countries and can accumulate Cd at a concentrations (in fresh weight) of 0.002 to 0.3 mg kg^{-1} (Kabata-Pendias and Mukherjee, 2007; McLaughlin et al., 1994a, 1994b; N. Kim, unpublished data, 2005), which is equivalent to 0.01 to 1.5 mg kg^{-1} dry weight (assuming a moisture content of 80%). A survey of potatoes grown in the Waikato Region of New Zealand was conducted (N. Kim, unpublished data, 2005) and showed that 1.5% of the

S.A. Mamun, N.J. Lehto, R. McDowell, M. Aktar, E. Benya, B.H. Robinson, Dep. of Soil Science, Faculty of Agricultural and Life Sciences, Lincoln Univ., PO Box 85084, Lincoln 7647, New Zealand; J. Cavanagh, Landcare Research, PO Box 69040, Lincoln 7640, Lincoln, New Zealand; R. McDowell, AgResearch, Invermay Agricultural Centre, Puddle Alley, Private Bag 50034, Mosgiel 9053, New Zealand. Assigned to Associate Editor Emmanuel Doelsch.

Abbreviations: CEC, cation exchange capacity; LM, lime; MC, municipal green waste compost; MS, mushroom industry residue compost; SC, shredded corn stover; SD, animal offal and sawdust compost.

potatoes exceeded the WHO and Australia and New Zealand Food Standard of 0.1 mg kg^{-1} fresh wt. (Bigdeli and Seilsepour, 2008; FSANZ, 2015). In Australia, McLaughlin et al. (1997) reported Cd concentrations more than double the guideline value (0.232 mg kg^{-1} fresh wt.) in potatoes in some samples. Per capita potato consumption rates in the United States, United Kingdom, Russia, Poland, Germany, and New Zealand are 55, 105, 110, 149, 146, and 66 kg yr^{-1}, respectively (Lisinska and Leszczynski, 1989; Russell et al., 1999). In high potato-consuming countries, even potato Cd concentrations below the permissible limits may also pose risk to human health (EFSA, 2012). Therefore, there is an imperative to reduce the transfer of Cd from soil to potato tubers.

Soil properties significantly affect the uptake of Cd by plants (Kabata-Pendias and Mukherjee, 2007; McLaughlin et al., 1994b; Merian, 1991). These properties can be modified by the use of soil amendments that have high numbers of functional groups that can reduce the phytoavailability of Cd (Pusz, 2007). Simmler et al. (2013) showed that certain organic amendments sorb significant amounts of Cd. In particular, composts have more than fourfold higher Cd sorption capacity than soils (Al Mamun et al., 2016). Increasing metal sorption in soil through the use of pH manipulation or introducing sorbing agents decreased the uptake of Cd by plants (Simmler et al., 2013; Valentinuzzi et al., 2015). Municipal composts reduced Cd uptake in spinach, lettuce, and onion by up to 60% (Al Mamun et al., 2016). Only one type of compost (municipal compost made from lawn clippings, tree pruning, and food debris) was tested in this study.

The use of composts may improve soil fertility and reduce the need for mineral fertilizers and associated Cd inputs. Composts improve the physical properties of soils by increasing total pore space, aggregate stability, nutrient- and water-holding capacity, erosion resistance, and temperature insulation and by decreasing apparent soil density. Composts can also improve the chemical properties of soils by modifying the soil pH (Sarwar et al., 2008; Shiralipour et al., 1992), cation exchange capacity (CEC), and soil nutrient content (Shiralipour et al., 1992) and can significantly increase the growth of plants (Barkoczi et al., 2008; Khan et al., 2007; Muhammad et al., 2007).

Depending on the soil properties, plant species, and application rates, liming can either decrease or increase the transfer of Cd from soil to plants in field conditions (Chaney et al., 2009; Hong et al., 2007; Maier et al., 1997; Tiller et al., 1997). Maier et al. (2002) observed that liming effectively reduced the accumulation of Cd in potato tubers in three soils where the initial pH of the soils ranged between 4.1 and 4.7. Maier et al. (1997) reported that when calcite lime was applied at a rate of 20 t ha^{-1} in field conditions and potato was grown, liming of the soil did not reduce the concentration of Cd in potato tuber. In some cases liming increased plant Cd uptake even though soil pH increased by two units. Shaheen and Rinklebe (2015) observed that liming the soil decreased the phytoavailable and exchangeable Cd in soil (Chen et al., 2016) but increased the concentration of Cd in rapeseed in the field trial (Shaheen and Rinklebe, 2015). The increase in Cd uptake may be due to an induced Zn deficiency at high soil pH, which persuades the plant to produce more root Zn transport proteins to obtain adequate soil Zn to check the Zn deficiency stress (Chaney et al., 2009). Because the Zn transport proteins also accumulate Cd, increased Zn transporting protein production by plants may cause even higher Cd accumulation during Zn deficiency stress in plants (Hart et al., 2002). Moreover, liming can create an imbalance among the nutrient elements in soil, specifically through significantly decreasing the concentration of essential nutrient elements K, Mn, B, and S (Maier et al., 2002).

We aimed to understand the influence of compost type and properties on the transfer of Cd from a soil (containing 1.5 mg kg^{-1} Cd) to potato (var. 'Nadine'). We sought to compare the effects of compost with lime added at 0.6 and 1.3% (w/w). Furthermore, we aimed to elucidate the effects of these soil amendments on the growth and nutrient uptake of potato.

Materials and Methods

Soils

We collected soil from a market garden in Pukekohe (37°13′18.92″ S, 174°52′5.94″ E) in the North Island of New Zealand. Samples were collected evenly across an area of 30 m^2 within the plow depth (0–0.25 m), and large stones and roots were removed manually. Soils were homogenized using a spade. A subsample was dried in an oven at 70°C for 1 wk, ground, and passed through a 2-mm plastic sieve before analysis. Table 1 shows the soil properties.

Composts and Lime

We used four commercially available composts made from contrasting raw materials (Table 1): municipal green waste compost (MC), animal offal and sawdust compost (SD), mushroom industry residue compost (MS), and pig manure and sawdust compost (PG). The effects of shredded corn stover (SC) and lime (LM) were also considered. Laboratory-grade dry lime powder (calcium carbonate) was used (AnalaR NORMAPUR, VWR, PROLABO).

Treatments

Soils were mixed with the following specific treatments: the composts and shredded corn stover at (w/w) application rates of 0% (control), 2.5% (Treatment 1), and 5% (Treatment 2) and lime at a rate of 0.6% (Treatment 1) and 1.3% (Treatment 2). All treatments were replicated three times. Liming rates were chosen following Valentinuzzi et al. (2015), who demonstrated these rates effectively reduced the Cd uptake by lupin (*Lupinus albus* L.). The pots were placed in a greenhouse in a randomized block design, where the temperature ranged between 15.6 and 27.4°C over the growth period.

Pot Trial

Seed potatoes (*Solanum tuberosum* 'Nadine') were purchased from a seed supplier (Morton and Smith). After a 7-d incubation in covered trays, the sprouted potatoes were planted on 18 Aug. 2014 in 5-L pots containing approximately 5 kg of soil (dry weight). Plants were watered daily in the morning up to field capacity, and weeds were removed manually. The potatoes were harvested when the plants showed symptoms of shoot dieback. For the SC-treated soils, this occurred 75 d after planting. All other treatments were harvested 60 d after planting. No fertilizers were applied before or during the growth period.

Soil samples were collected at the time of harvesting potatoes from each pot. Care was taken to avoid scratching the potato tubers. The aboveground portions and the tubers were separated and washed three times with tap water followed by three

Table 1. Physico-chemical properties of soil and soil amendments (includes total elements digested by concentrated HNO_3).

Properties	Soil amendments†					Pukekohe soil
	SC	MC	MS	SD	PG	
Source	a local farm at Leeston, Christchurch, NZ	Living Earth Ltd., Christchurch, NZ	Christchurch, NZ			from a commercial vegetable garden at Pukekohe, Auckland, NZ (37°13′18.92″ S, 174°52′5.94″ E)
Raw ingredients	corn stover	municipal compost originated from municipal green waste, including lawn mowing and tree pruning	residual compost waste generated by the mushroom production industry	animal residues and sawdust	pig manure added with sawdust	soil
pH (H_2O)	5.5 (0.2)‡	7.3 (0.06)	6.8 (0.01)	7.1 (0.2)	7.0 (0.01)	5.9 (0.02)
CEC, $cmol_c$ kg^{-1}	11 (1)	46 (2)	42 (3)	46 (2)	44 (1)	21 (2)
Moisture, %	30 (2)	24 (3)	73 (4)	42 (3)	42 (2)	25 (2)
C, %	47 (2)	19 (2)	34 (3)	20 (2)	41 (3)	2.2 (0.3)
N, %	0.09 (0.02)	2.0 (0.3)	2.0	1.4 (0.2)	1.2	0.24 (0.01)
P, mg kg^{-1}	341 (16)	4,120 (40)	4,860 (116)	4,879 (198)	6,559 (357)	3,424 (31)
S, mg kg^{-1}	642 (13)	2,547 (110)	16,352 (74)	3,725 (140)	2,618 (61)	498 (15)
Ca, mg kg^{-1}	1,907 (48)	25,132 (434)	67,427 (1,131)	37,159 (981)	10,372 (298)	4,170 (149)
Mg, mg kg^{-1}	503 (6.4)	4,217 (150)	2,957 (100)	2,431 (122)	2,790 (52)	2,464 (91)
K, mg kg^{-1}	19,666 (13)	14,351 (149)	7,306 (91)	5,119 (172)	5,882 (106)	1,995 (53)
B, mg kg^{-1}	<0.0003	18 (2)	13 (0.07)	<0.0003	20 (0.3)	28 (4)
Cd, mg kg	<0.00026	0.68 (0.1)	0.24 (0.07)	0.47 (0.1)	0.16 (0.027)	1.5 (0.03)
Cu, mg kg^{-1}	2.3 (0.35)	57 (1)	68 (2.6)	27 (1)	296 (0.43)	64 (1)
Zn, mg kg^{-1}	18 (1.9)	319 (20)	230 (2.5)	35 (2)	304 (13)	174 (4)
Cr, mg kg^{-1}	1.02 (0.60)	28 (1)	18 (0.10)	39 (1)	3.0 (0.48)	42 (1)
Ni, mg kg^{-1}	0.89 (0.20)	10 (2)	4 (0.2)	6 (2)	2.4 (0.03)	21 (1)
Fe, %	0.01 (0.00)	1.24 (0.03)	0.42 (0.00)	0.82 (0.02)	0.17 (0.00)	5.42 (0.06)

† MC, municipal green waste compost; MS, mushroom industry residue compost; PG, pig manure and sawdust compost; SC, shredded corn stover; SD, animal offal and sawdust compost.

‡ Standard errors are given in parentheses ($n = 3$).

washings with deionized water. The tubers were dried with paper towels, the fresh weights of the tubers were obtained.

The potato skin (1–2 mm) was separated using a clean stainless steel knife, and the potato was cut in to small pieces to facilitate grinding. The aboveground portions were separated in to shoots and leaves. All plant parts were kept in labeled paper envelopes and left in an oven at 70°C until a constant weight was obtained (~1 wk). Paper envelopes were immediately transferred to sealed polythene sacks to prevent absorption of moisture from the air. After weighing and grinding, samples were placed in sealed plastic vials before analysis.

Chemical Analysis

Soil pH was determined using 10 g of soil and 25 mL of deionized 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 and shredded corn stover). The mixture was shaken, left to equilibrate for 24 h before measurement and shaken again before determination with a pH meter (Mettler Toledo Seven Easy) (Blakemore, 1987). We measured CEC using the 0.01 M Silver Thiourea (AgTU) method (Blakemore, 1987). An Elementar Vario-Max CN analyzer was used to analyze the total carbon and nitrogen content in the soil and compost samples.

The phytoavailable fraction of Cd in the soils was determined using a modified 0.05 M $Ca(NO_3)_2$ extraction based on Black et al. (2012) and Gray et al. (1999a, 199b). Briefly, in a centrifuge tube, 5 g of soil was mixed with 30 mL of extractant using a vortex mixer, and a suspension was formed. The centrifuge tube was agitated for 2 h using an end-over-end shaker and then centrifuged at 3000 rpm for 15 min. The supernatant was filtered through Whatman no. 52 filter paper and frozen until analysis.

Pseudo-total elemental analyses of plants were performed using microwave digestion (MARSXPRESS, CEM Corp.) of 0.5 g of plant sample in 8 mL of Aristar nitric acid (±69%) and filtered through Whatman no. 52 filter paper (pore size, 7 μm) after dilution with milliQ water to a volume of 10 mL. For soils, a block digest method was used following the procedure of Kovács et al. (2000). We also analyzed Certified Reference Materials for soil (International Soil analytical Exchange- ISE 921) and plant (International Plant analytical Exchange IPE 100) from Wageningen University, The Netherlands.

Concentrations of Cd, Ca, Mg, K, S, B, Cu, P, Pb, Zn, Cr, Ni, and Zn were determined using inductively coupled plasma optical emission spectrometry (Varian 720 ES- USA) in soils (Kovács et al., 2000) and in plants (Simmler et al., 2013; Valentinuzzi et al., 2015). Extraction and digestion solution and method blanks were analyzed in triplicate as part of standard quality control procedure for the analysis and were as below the detection limit of inductively coupled plasma optical emission spectrometry for all metals. Recoverable concentrations of the Certified Reference Materials were within 93 to 110% of the certified values.

Statistical Analysis

We used Minitab 17 (Minitab Inc.) and Microsoft Excel 2013 to analyze data. Analysis of variance with Fisher's LSD post hoc test was used to assess the effects of different treatments. The significance level for all statistical analyses was $P < 0.05$.

Results

Effect of Amendments on Cd Concentration in Peeled Potato Tubers

The Cd concentration in the peeled tubers ranged from 0.01 to 0.04 mg kg^{-1} dry wt. (Fig. 1), which is at the lower end of the range of 0.01 to 1.50 mg kg^{-1} dry wt. reported in the literature (Kabata-Pendias and Mukherjee, 2007; Kim, 2008; McLaughlin et al., 1994a, 1994b). The moisture content in our potatoes was 82% (w/w). Therefore, the fresh weight Cd concentrations of the tubers ranged from 0.002 to 0.008 mg kg^{-1}. This Cd concentration is well below the World Health Organization's and Food Standards of Australia and New Zealand's limit for Cd in vegetables of 0.1 mg kg^{-1} (fresh wt.) (Bigdeli and Seilsepour, 2008; FSANZ, 2015) and the Codex limit of 0.1 mg kg^{-1} fresh wt. for potatoes (Codex, 2011; Codex, 2015).

All the composts significantly decreased ($P < 0.05$) the concentration of Cd in peeled tubers (29–73%) compared with the control (Fig. 1). The greatest reduction in the Cd concentration compared with the control was achieved by the SC treatment (71%). Potatoes grown in soils treated with PG, MS, SD, and MC accumulated less Cd (58–66%, 46–63%, 52–53%, and 29–49%, respectively) in the potato flesh compared with the control. The 0.6 and 1.3% lime treatments decreased Cd concentration in the peeled tubers (by 43–54%).

Cadmium in Potato Skins and Shoots

The Cd concentration in potato skins varied from 0.02 to 0.09 mg kg^{-1} dry wt. (Fig. 2). All treatments in soil significantly decreased the concentration of Cd in potato skins except the potato skins grown in soils treated with MC1 and PG2 (Fig. 2). The greatest reduction (85%) in the potato skin Cd concentration was observed in soils treated with SC2, followed by soils treated with SC1 (70% reduction), SD2 (63% reduction), and L1 (62% reduction). No significant difference was observed in the concentration of Cd in potato skin grown in the two rates of soil amendments except MC-treated soils, where potato skins of potato grown in MC2-treated soils had significantly less Cd concentration than that of MC1-treated soils.

The Cd concentrations in the potato stems ranged from 0.18 to 0.94 mg kg^{-1} dry wt. (Supplemental Table S1). Both the rates of MC and SD and the 2.5% rate of PG significantly reduced the concentration of Cd in potato stem (by 62, 66, 62, 67, and 66%, respectively), whereas SC1 increased the concentration of Cd compared with control. The Cd concentrations in the potato leaves ranged from 0.11 to 0.27 mg kg^{-1} dry wt. (Supplemental Table S2). Both the rates of SC and LM 1 significantly decreased the concentration of Cd in potato leaves by 52, 56, and 51%, respectively.

Concentrations of Other Elements

Unlike Cd, the treatments had no consistent effect on the other elements in the tubers, peel, stems, or leaves (Tables 2–5; Supplemental Tables S1 and S2). The concentration of B

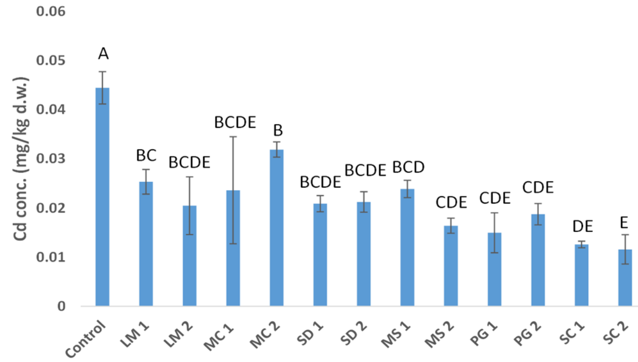

Fig. 1. Cadmium concentration in potato tubers (dry weight basis). Error bars represent SEM (*n* = 3). Values with the same letters are not significantly different.

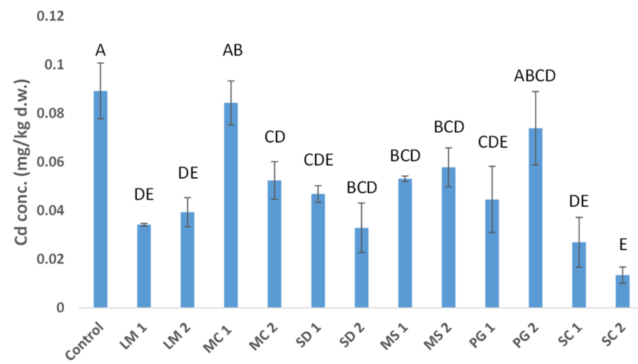

Fig. 2. Cadmium concentration in potato skins (dry weight). Bars represent SEM (*n* = 3). Values with the same letters are not significantly different.

decreased in potato tubers grown in soils treated with both rates of LM and SC (Table 3). The Zn concentration in potato tubers ranged from 16.7 to 23.0 mg kg^{-1}, and no consistent differences were observed for Zn accumulation in potato tuber compared with control. There were no significant differences in the concentration of P in the potato tubers, skins, or stems. Phosphorous in potato leaves increased in the SC treatments. All the treatments reduced the Zn and Fe concentrations in potato skins.

Effect of Treatments on Potato Growth

Composts significantly increased the growth of both tubers and shoots (Fig. 3 and 4). The LM treatments significantly increased the tuber growth but decreased the shoot growth. Treatment with SC decreased potato tuber and shoot growth. An unpleasant odor emanated from the SC soil, indicating that it may have turned anaerobic after approximately 3 wk, which may explain the poor yield. The highest tuber growth was observed in soils treated with MC2 (168% increase), followed by soils treated with PG1 (112% increase), MS2 (109% increase), MC1 (106% increase), MS1 (102%), PG2 (67%), SD2 (63%), SD1 (47%), LM1 (45%), and LM2 (33%). The addition of SC1 and SC2 decreased potato growth by 50 and 60%, respectively.

Effect of Treatments on Soil Properties

Table 6 shows that all treatments increased pH except SD1, SD2, PG2, and SC1, which had no significant effect on pH. The LM treatments resulted in by far the largest pH increase by 1.0 to 1.2 pH units, respectively, whereas the composts either had no effect or resulted in a slight increase (<0.4 pH units). All the

Table 2. Elemental composition of the peeled potato tubers: macronutrients.

Treatment†	% C	% N	Ca	K	Mg	P (ns)‡	S
			mg kg^{-1}				
Control	40.59 (0.193)ab§	0.83 (0.075)b	419 (65)abc	20,811 (424)bcd	1,268 (72)bcd	3,356 (179)	1,248 (71)ef
LM 1	40.34 (0.189)abc	0.85 (0.034)b	436 (42)ab	19,428 (526)cd	1,134 (29)d	3118 (116)	1,338 (60)cdef
LM 2	40.70 (0.197)a	0.96 (0.062)b	518 (66)a	18,791 (867)d	1,137 (28)d	3,088 (170)	1,366 (56)cdef
MC 1	40.24 (0.257)abc	0.91 (0.022)b	289 (15)cd	21,565 (705)abc	1,253 (39)bcd	3,245 (60)	1,214 (37)f
MC 2	39.98 (0.099)c	0.98 (0.034)b	258 (22)d	21,640 (123)abc	1,217 (19)cd	3,163 (111)	1,275 (38)def
SD 1	40.07 (0.099)c	0.86 (0.065)b	307 (18)bcd	20,414 (694)bcd	1,227 (17)cd	3,284 (21)	1,295 (60)def
SD 2	40.33 (0.046)abc	0.93 (0.040)b	308 (53)bcd	21,229 (11081)abc	1,330 (37)abc	3,264 (267)	1,405 (48)cdef
MS 1	40.19 (0.157)bc	0.88 (0.108)b	418 (55)abc	20,011 (185)cd	1,201 (60)cd	3,026 (88)	1,539 (83)bcd
MS 2	40.25 (0.083)abc	0.85 (0.031)b	320 (23)bcd	21,600 (1,476)abc	1,294 (34)bc	3,014 (43)	1,593 (53)bc
PG 1	40.63 (0.109)ab	0.95 (0.035)b	298 (33)cd	22,611 (757)ab	1,473 (18)a	3,397 (12)	1,531 (24)bcde
PG 2	40.65 (0.255)ab	1.01 (0.104)b	420 (57)abc	20,464 (414)bcd	1,386 (69)ab	3,082 (61)	1,452 (100)cdef
SC 1	39.37 (0.165)d	1.40 (0.152)a	326 (48)bcd	21,622 (988)abc	1,143 (101)d	3,134 (87)	1,757 (209)ab
SC 2	39.44 (0.161)d	1.55 (0.292)a	376 (49)bcd	23,203 (1039)a	1,239 (36)cd	3,327 (340)	1,900 (206)a

† Control, no treatment in soil; LM 1 and LM 2, lime 0.6 and 1.3%, respectively; MC 1 and MC 2, municipal green waste compost 2.5 and 5%, respectively; MS 1 and MS 2, mushroom industry residue compost 2.5 and 5%, respectively; PG 1 and PG 2, pig manure composted with sawdust 2.5 and 5%, respectively; SC 1 and SC 2, shredded corn stover 2.5 and 5%, respectively; SD 1 and SD 2, sawdust composted with animal offal 2.5 and 5%, respectively.

‡ ns, no significant differences between P concentrations.

§ Standard errors are given in parentheses (n = 3). Values in the same column with the same letters are not significantly different.

Table 3. Elemental composition of the peeled potato tubers: micronutrients.

Treatment†	B	Cr	Cu	Fe	Mn	Mo	Na	Zn
				mg kg^{-1}				
Control	7.40 (0.04)a‡	0.624 (0.04)a	6.1 (0.3)ab	23 (2)ab	6.96 (0.7)abc	0.6 (0.05)d	87 (16)cd	20 (2)abc
LM 1	6.37 (0.2)bc	0.484 (0.2)abc	5.9 (0.2)b	19 (0.8)b	6.04 (0.2)c	2.1 (0.1)a	110 (13)abcd	18 (0.4)bcd
LM 2	6.43 (0.04)bc	0.463 (0.06)abc	6.2 (0.4)ab	19 (1)b	5.95 (0.1)c	2.1 (0.2)a	83 (4)d	18 (0.8)bcd
MC 1	7.33 (0.3)a	0.266 (0.02)bcd	6.4 (0.4)ab	21 (0.2)b	6.7 (0.2)abc	1.4 (0.2)b	153 (1)abc	19 (1)bcd
MC 2	6.72 (0.3)abc	0.469 (0.1)abc	6.6 (0.3)ab	21 (0.1)ab	6.3 (0.1)c	1.3 (0.2)bc	173 (34)a	19 (0.6)bcd
SD 1	6.80 (0.1)abc	0.467 (0.2)abc	5.8 (0.2)b	20 (1)b	6.8 (0.2)abc	0.63 (0.1)cd	98 (20)bcd	17 (0.3)cd
SD 2	6.89 (0.2)ab	0.495 (0.07)ab	6.6 (0.2)ab	23 (0.3)ab	7.5 (0.2)ab	1.2 (0.1)bc	152 (47)abc	18 (1)bcd
MS 1	6.66 (0.4)abc	0.212 (0.04)d	6.8 (0.5)ab	19 (0.7)b	6.4 (0.4)bc	0.6 (0.04)d	140 (31)abcd	17 (0.4)cd
MS 2	6.61 (0.3)abc	0.18 (0.1)d	6.3 (0.2)ab	18 (0.9)b	6.0 (0.2)c	0.57 (0.2)d	135 (25)abcd	16 (0.5)d
PG 1	6.74 (0.1)abc	0.169 (0.1)d	6.1 (0.1)ab	21 (0.6)b	7.0 (0.1)abc	0.8 (0.07)bcd	110 (10)abcd	18 (0.3)cd
PG 2	6.95 (0.3)ab	0.238 (0.03)cd	6.1 (0.4)ab	20 (0.7)b	6.4 (0.3)bc	0.9 (0.02)bcd	158 (21)ab	17 (1)cd
SC 1	5.99 (0.3)cd	0.105 (0.02)d	7.6 (0.5)a	21 (2.5)ab	6.7 (0.9)abc	1.1 (0.5)bcd	89 (12)cd	22 (2)ab
SC 2	5.39 (0.4)d	0.241 (0.1)cd	7.4 (1.5)ab	27 (5)a	7.6 (0.6)a	1.4 (0.5)b	120 (14)abcd	23 (3)a

† Control, no treatment in soil; LM 1 and LM 2, lime 0.6 and 1.3%, respectively; MC 1 and MC 2, municipal green waste compost 2.5 and 5%, respectively; MS 1 and MS 2, mushroom industry residue compost 2.5 and 5%, respectively; PG 1 and PG 2, pig manure composted with sawdust 2.5 and 5%, respectively; SC 1 and SC 2, shredded corn stover 2.5 and 5%, respectively; SD 1 and SD 2, sawdust composted with animal offal 2.5 and 5%, respectively.

‡ Standard errors are given in parentheses (n = 3). Values in the same column with the same letters are not significantly different.

composts significantly increased C and N, and there was a small increase in the C/N ratio in all treatments.

All of the organic amendments reduced $Ca(NO_3)_2$–extractable Cd in the soil, except PG2 (Table 7). The effect of the composts on the $Ca(NO_3)_2$–extractable concentrations of other elements was variable, with the changes reflecting the composition of the composts (Table 1). The LM treatments caused an approximately 10-fold decrease in $Ca(NO_3)_2$–extractable Zn, whereas the effect of the composts was smaller and in many cases not significant (Table 7)

Discussion

The low Cd concentrations in the potato tubers was not anticipated because the soil Cd concentration (1.48 mg kg^{-1}) is within the top 5% of New Zealand soils (Reiser et al., 2014), although the same low concentration was observed in the potato tubers in New Zealand soils by Kim (2008) and in Australia by Maier et al. (2002). In contrast to the tubers, the Cd concentrations in the stems and leaves of potato were with the range (0.2–0.9 mg kg^{-1}) of concentrations reported by Maier et al. (2002). This indicates that the low concentration of Cd in the tubers is the result of plant physiological processes rather than low Cd bioavailability in the soil. Given that Cd is relatively phloem immobile (Uraguchi et al., 2009), one would not expect high Cd concentrations in the tubers, which receive most of their nutrients via the phloem (Dunbar et al., 2003).

The lower tuber Cd concentrations in our study compared withthose reported by other authors (Kabata-Pendias and Mukherjee, 2007; McLaughlin et al., 1994a, 1994b; N. Kim, unpublished data, 2005) may be due to differences in variety, although McLaughlin

Table 4. Elemental composition of the potato skin: macronutrients.

Treatment†	Ca	K	Mg	P (ns)‡	S
	mg kg^{-1}				
Control	1,286 (155)b§	37,687 (1,278)a	2,063 (146)ab	5,327 (269)	1,647 (150)abc
LM 1	1,690 (224)ab	27,967 (921)e	1,504 (72)b	4,540 (176)	1,394 (55)c
LM 2	1,909 (19)ab	30,785 (1,623)cde	1,733 (61)b	5,000 (209)	1,607 (82)bc
MC 1	925 (114)b	35,960 (1,956)ab	1,811 (46)b	5,269 (327)	1,388 (14)c
MC 2	859 (17)b	35,257 (614)abc	1,750 (74)b	5,058 (96)	1,452 (76)c
SD 1	1,018 (166)b	33,589 (1071)abcd	1,711 (115)b	5,298 (373)	1,482 (101)c
SD 2	1,232 (46)b	31,632 (2983)bcde	2,039 (98)ab	5,075 (565)	1,676 (64)abc
MS 1	1,252 (79)b	32,001 (1101)bcde	1,801 (52)b	4,972 (128)	2,129 (25)a
MS 2	1,084 (75)b	32,503 (1229)bcde	1,601 (50)b	4,594 (109)	1,809 (39)abc
PG 1	890 (79)b	32,041 (1624)bcde	1,784 (89)b	5,177 (172)	1,435 (113)c
PG 2	3,540 (23)a	34,002 (1104)abcd	2,534 (730)a	4,946 (195)	2,045 (474)ab
SC 1	840 (37)b	34,760 (1914)abcd	1,498 (226)b	4,496 (522)	1,546 (238)c
SC 2	931 (79)b	30,190 (2899)de	1,463 (72)b	4,401 (723)	1,789 (175)abc

† Control, no treatment in soil; LM 1 and LM 2, lime 0.6 and 1.3%, respectively; MC 1 and MC 2, municipal green waste compost 2.5 and 5%, respectively; MS 1 and MS 2, mushroom industry residue compost 2.5 and 5%, respectively; PG 1 and PG 2, pig manure composted with sawdust 2.5 and 5%, respectively; SC 1 and SC 2, shredded corn stover 2.5 and 5%, respectively; SD 1 and SD 2, sawdust composted with animal offal 2.5 and 5%, respectively.

‡ ns, no significant differences between P concentrations.

§ Standard errors are given in parentheses ($n = 3$). Values in the same column with the same letters are not significantly different.

Table 5. Elemental composition of the potato skin: micronutrients.

Treatment†	B	Cr	Cu	Fe	Mn	Mo	Zn
	mg kg^{-1}						
Control	15.3 (1)a‡	0.4 (0.1)a	7.5 (0.4)bc	353 (115)a	20 (5)a	0.6 (0.1)cd	42 (10)a
LM 1	9.8 (0)de	0.1 (0.03)c	7.0 (0.1)c	77 (18)b	7 (0.1)b	1.9 (0.1)a	22 (2)b
LM 2	11.6 (1)bcde	0.2 (0.02)b	7.9 (0.6)bc	53 (3)b	8 (0.4)b	1.9 (0.1)a	24 (1)b
MC 1	13 (1)abc	0.1 (0.03)c	8.8 (0.5)abc	119 (33)b	9 (1.4)b	1.1 (0.1)bc	25 (3)b
MC 2	12.6 (0)bc	0.1 (0.02)c	9.5 (0.3)ab	98 (32)b	9 (1.3)b	1.1 (0.1)bc	25 (2)b
SD 1	12.7 (1)bc	0.1 (0.02)c	8.2 (0.7)bc	98 (22)b	10 (0.8)b	0.5 (0.1)cd	22 (2)b
SD 2	12.1 (1)bcd	0.2 (0.03)b	8.5 (0.5)abc	109 (11)b	10 (1.5)b	1.1 (0.1)bc	22 (3)b
MS 1	11.9 (1)bcde	0.1 (0.03)c	9.3 (0.4)abc	133 (42)b	10 (1)b	0.5 (0.1)cd	20 (0)b
MS 2	10.8 (1)cde	0.1 (0.01)c	8.8 (0.5)abc	50 (8)b	7 (0.8)b	0.4 (0.1)d	19 (0)b
PG 1	11.1 (0)bcde	0.1 (0.02)c	8.6 (0.1)abc	67 (9)b	7 (0.1)b	0.7 (0.1)cd	20 (1)b
PG 2	13.5 (0)ab	0.2 (0.08)bc	9.6 (1.1)ab	161 (73)b	12 (2.2)b	0.8 (0.2)bcd	24 (3)b
SC 1	11.5 (2)bcde	0.1 (0.01)c	9 (1.4)abc	49 (11)b	8 (3)b	1.1 (0.4)bc	28 (5)b
SC 2	9.6 (1)e	0.1 (0.01)c	10.7 (1.9)a	40 (12)b	9 (0.3)b	1.4 (0.5)ab	24 (3)b

† Control, no treatment in soil; LM 1 and LM 2, lime 0.6 and 1.3%, respectively; MC 1 and MC 2, municipal green waste compost 2.5 and 5%, respectively; MS 1 and MS 2, mushroom industry residue compost 2.5 and 5%, respectively; PG 1 and PG 2, pig manure composted with sawdust 2.5 and 5%, respectively; SC 1 and SC 2, shredded corn stover 2.5 and 5%, respectively; SD 1 and SD 2, sawdust composted with animal offal 2.5 and 5%, respectively.

‡ Standard errors are given in parentheses ($n = 3$). Values in the same column with the same letters are not significantly different.

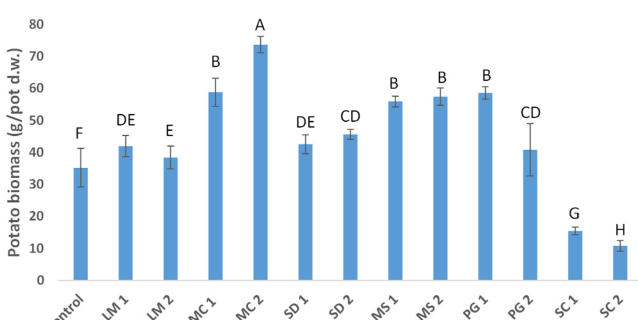

Fig. 3. Tuber biomass (including skins). Bars represent SEM ($n = 3$). Values with the same letters are not significantly different.

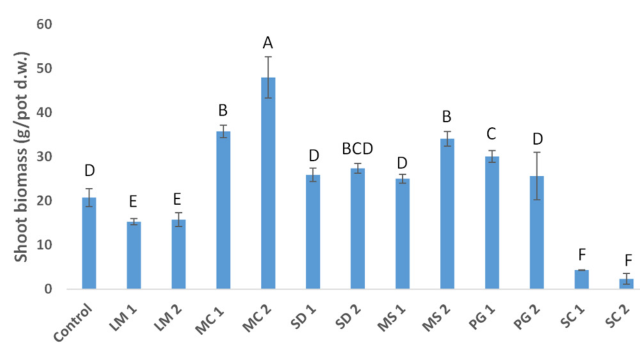

Fig. 4. Shoot biomass (dry weight [d.w.]). Bars represent SEM ($n = 3$). Values with the same letters are not significantly different.

et al. (1994a) reported only small differences in Cd uptake between varieties. In our study, the potatoes were peeled with a knife to ensure that no skin and associated soil particles remained on the tuber. Knife peeling removes a greater portion of the tuber than a typical peeler. If the potato flesh directly under the skin has a higher Cd concentration than the remainder of the tuber, then this would explain our lower Cd results in our study.

The concentration ratio of the potato flesh:skin/peel:shoots was 2:5:29, with little variation between treatments. This is similar to other experiments with potato (Corguinha et al., 2012; Reid et al., 2003). Some of Cd in potato skins may arise from the incorporation of soil particles into the skin that could not be removed even after washing.

All amendments significantly reduced Cd uptake by the potato tubers and most amendments reduced uptake into the shoots. A similar result was also observed by Kim et al. (2016), who observed a reduction in the accumulation of Cd due to the application of lime and peat, although in their experiment the soil had exceptionally higher Cd concentration than in our experiment (55 mg Cd kg^{-1} soil vs. 1.5 mg Cd kg^{-1} soil) where the Cd concentration was elevated due to the application of P fertilizers in New Zealand agricultural soils (Taylor, 1997). The reduction in Cd uptake may be partially explained by the reduction in bioavailable Cd [estimated in our experiments using a 0.05 M $Ca(NO_3)_2$ extraction], which occurred in all of the treatments and which has been reported by other authors with different plants (Pandit et al., 2012) and soils (Kim et al., 2016; Pandit et al., 2012). Black et al. (2012) and Gray et al. (1999a, 1992b) reported a strong positive correlation between plant Cd and $Ca(NO_3)_2$–extractable Cd in a single soil type.

For the MC, MS, and PG1 treatments, the reduced Cd concentration in the tubers may be partly explained by the small

Table 6. Soil pH, total C and N, and 0.05 M $Ca(NO_3)_2$–extractable macronutrient elements.

Treatment†	pH	Total C	Total N	C/N	K	Mg	P	S
		——— % ———			——— mg kg^{-1} ———			
Control	6.04 (0.02)gh‡	2.29 (0.02)g	0.212 (0.003)fg	10.84 (0.021)efg	258 (13)h	426 (18)e	3.85 (0.3)fg	219 (57)d
LM 1	7.03 (0.58) b	2.28 (0.13)g	0.206 (0.002)fg	11.06 (0.046)def	271 (5)gh	291 (1)f	3.99 (0.01)fg	231 (23)d
LM 2	7.28 (0.03)a	2.29 (0.03)g	0.185 (0.009)g	12.47 (0.540)bc	244 (6)h	247 (2)g	4.01 (0.14)fg	200 (16)d
MC 1	6.26 (0.02)e	3.00 (0.08)ef	0.285 (0.007)bc	10.53 (0.128)fg	305 (3)fg	493 (4)cd	4.27 (0.03)def	184 (11)d
MC 2	6.37 (0.03 cd	4.07 (0.16)a	0.403 (0.018)a	10.12 (0.070)g	408 (5)cd	569 (13)ab	4.88 (0.1)bc	155 (7)d
SD 1	6.09(0.01)fgh	3.21 (0.04)de	0.269 (0.006)cd	11.93 (0.257)cd	267 (4)h	431 (7)e	4.10 (0.2)efg	146 (12)d
SD 2	6.13 (0.05)fg	4.12 (0.08)a	0.309 (0.009)b	13.34 (0.172)ab	258 (20)h	452 (6)de	4.54 (0.3)cde	135 (9)d
MS 1	6.28 (0.03)de	3.84 (0.02)ab	0.247 (0.002)de	11.84 (0.007)cd	374 (14)de	535 (8)bc	4.79 (0.1)bc	1064 (53)b
MS 2	6.43 (0.01)c	2.93 (0.10)ef	0.302 (0.007)b	12.70 (0.071)bc	422 (2)c	612 (6)a	5.70 (0.1)a	1521 (54)a
PG 1	6.30 (0.05)de	2.86 (0.04)f	0.231 (0.015)ef	12.43 (0.690)bc	573 (24)b	430 (9)e	3.73 (0.1)g	47 (4)d
PG 2	6.10 (0.03)fgh	3.67 (0.11)bc	0.264 (0.008)cd	13.90 (0.532)a	769 (9)a	504 (21)c	4.67 (0.1)bcd	96 (8)d
SC 1	6.01 (0.01)h	2.92 (0.11)f	0.255 (0.007)de	11.46 (0.128)de	313 (5)f	452 (8)de	4.87 (0.1)bc	287 (37)d
SC 2	6.14 (0.04)f	3.45 (0.22)cd	0.306 (0.020)b	11.27 (0.187)def	372 (16)e	502 (15)c	5.02 (0.1)b	559 (88)c

† Control, no treatment in soil; LM 1 and LM 2, lime 0.6 and 1.3%, respectively; MC 1 and MC 2, municipal green waste compost 2.5 and 5%, respectively; MS 1 and MS 2, mushroom industry residue compost 2.5 and 5%, respectively; PG 1 and PG 2, pig manure composted with sawdust 2.5 and 5%, respectively; SC 1 and SC 2, shredded corn stover 2.5 and 5%, respectively; SD 1 and SD 2, sawdust composted with animal offal 2.5 and 5%, respectively.

‡ Standard errors are given in parentheses (n = 3). Values in the same column with the same letters are not significantly different.

Table 7. The 0.05 M $Ca(NO_3)_2$–extractable Cd, Na, and micronutrient elements of the soils.

Treatment†	Cd	Cu	Fe	Mn	Na	Zn
			mg kg^{-1}			
Control	0.011 (0.003)a‡	0.16 (0.014)def	0.20 (0.04)c	23 (2)de	118 (9)ef	0.419 (0.03)a
LM 1	0.002 (0.001)de	0.21 (0.005)ab	0.34 (0.15)bc	6 (2)fg	92 (0.2)g	0.032 (0.01)e
LM 2	0.009 (0.000)e	0.20 (0.004)bc	0.41 (0.1)abc	3 (0.6)g	89 (1)g	0.055 (0.02)e
MC 1	0.002 (0.000)de	0.17 (0.015)de	0.34 (0.11)bc	14 (0.2)ef	200 (4)b	0.322 (0.04)abc
MC 2	0.001 (0.000)e	0.17 (0.018)cde	0.43 (0.13)abc	14 (2)efg	245 (3)a	0.215 (0.04)cd
SD 1	0.006 (0.000)b	0.15 (0.015)efg	0.19 (0.02)c	23 (4)de	114 (5)f	0.323 (0.01)abc
SD 2	0.003 (0.000)cde	0.13 (0.013)fg	0.14 (0.06)c	23 (2)de	123 (4)ef	0.251 (0.03)bcd
MS 1	0.004 (0.000)cd	0.24 (0.006)a	0.17 (0.1)c	33 (7)cd	146 (4)d	0.175 (0.03)cde
MS 2	0.001 (0.000)e	0.24 (0.001)a	0.30 (0.01)bc	17 (0.3)e	179 (4)c	0.148 (0.08)de
PG 1	0.006 (0.001)b	0.13 (0.001)g	0.43 (0.01)abc	44 (2)ab	89 (4)g	0.457 (0.11)a
PG 2	0.009 (0.002)a	0.15 (0.003)defg	0.53 (0.2)ab	49 (8)a	127 (6)ef	0.419 (0.09)a
SC 1	0.005 (0.001)bc	0.19 (0.003)bcd	0.38 (0.03)abc	38 (3)bc	135 (6)de	0.475 (0.06)a
SC 2	0.001 (0.000)e	0.17 (0.001)cde	0.69 (0.02)a	29 (0.4)cd	173 (3)c	0.403 (0.05)ab

† Control, no treatment in soil; LM 1 and LM 2, lime 0.6 and 1.3%, respectively; MC 1 and MC 2, municipal green waste compost 2.5 and 5%, respectively; MS 1 and MS 2, mushroom industry residue compost 2.5 and 5%, respectively; PG 1 and PG 2, pig manure composted with sawdust 2.5 and 5%, respectively; SC 1 and SC 2, shredded corn stover 2.5 and 5%, respectively; SD 1 and SD 2, sawdust composted with animal offal 2.5 and 5%, respectively.

‡ Standard errors are given in parentheses (n = 3). Values in the same column with the same letters are not significantly different.

increase in pH of the amended soils (Table 6). However, most of the decrease in tuber Cd may be attributed to the increase in Cd-binding sites on the composts, which is indicated by their high CEC values (Table 1). The CEC of the composts in this study was similar to those reported in other composts and organic amendments (Pusz, 2007; Simmler et al., 2013). The increase in CEC in the amended soils is likely due to the high concentration of organic C in the composts (20–47%) compared with the soil (2.2%). Although Fe oxides are important for Cd binding in soil (Covelo et al., 2007), the Fe concentrations in the composts tested were an order of magnitude less than the soil (Table 1). For all treatments except the SC, the increased growth of the tuber may have resulted in a lower Cd concentration due to a "dilution effect" (Robinson et al., 2009). This effect may also explain the increased shoot Cd in the SC1 treatment where the shoot growth was significantly reduced.

It is unlikely in this study that Zn reduced Cd uptake by alleviating Zn deficiency because the soil contained 174 mg kg^{-1} Zn (Table 1), which is more than double the mean Zn concentration in New Zealand pastoral soils (65 mg kg^{-1}) (Reiser et al., 2014). Nevertheless, in Zn-deficient soils, the higher Zn concentrations (>200 mg kg^{-1}) of the MC may supply sufficient Zn to reduce plant Cd uptake. The MS and PG amendments may reduce Cd uptake by reducing the expression plant Zn transport proteins (which also transport Cd) that are produced in Zn-deficient environments (Chaney et al., 2009).

The reduction of Cd concentration in potato flesh grown in LM treatments was anticipated because these two rates of lime were selected from a previous study using the same soil, where the effects of seven rates of lime treatment were tested on the Cd solubility and uptake by white lupin (Valentinuzzi et al., 2015). Lime treatments in soil have been reported to both increase and decrease the uptake of Cd by plants. Lime significantly increased soil pH (Table 6), which has been associated with decreasing the accumulation of Cd in plants in almost all studies (Hong et al., 2007; Kabata-Pendias and Mukherjee, 2007; Kim et al., 2016; Simmler et al., 2013) through increasing the availability of negative binding sites on variable charged soil moieties (Brady and Weil, 2008) that may bind Cd. Our results stand in contrast to other studies that reported an increased uptake of Cd by plants due to lime application, which was attributed to competition between Cd and Ca for sorption sites in soil (Chaney et al., 2009; Maier et al., 2002; McLaughlin et al., 1997; Merian, 1991).

A positive growth response to compost addition has also been shown by other authors (Barkoczi et al., 2008; Khan et al., 2007; Muhammad et al., 2007). The composts used in this study contained high P content compared with the soil, and thus no fertilizer was used, which eliminated the risk of further addition of Cd input in this soils. Moreover, this compost probably improved the physical properties of soils by improving soil porosity, aggregate stability, nutrient- and water-holding capacity, and temperature insulation and by decreasing apparent soil density (Sarwar et al., 2008; Shiralipour et al., 1992) and soil nutrient content (Shiralipour et al., 1992). The reduced shoot growth in the lime treatment may have been due to the imbalance of nutrient elements in soil due to the pH increase (Maier et al., 2002).

Conclusions

Composts with contrasting provenances all decreased the concentration of Cd in potato tubers and skins and decreased the $Ca(NO_3)_2$–extractable concentrations of Cd in soil. Most of this effect was attributed to the increased number binding sites for Cd in compost-amended soil. In addition, the increase in fertility associated with compost addition may have reduced potato Cd concentrations by increasing the biomass, thereby resulting in a "dilution by growth" effect. All composts and lime significantly increased tuber growth except SC, which significantly reduced growth. That all the composts in this study reduced Cd uptake does not imply that every compost will do so. Further work is warranted to identify the key components of composts that result in reduced Cd uptake by plants and increased biomass of potato. Potentially, composts may be a low-cost means of ensuring that crop Cd concentrations remain within Food Safety Standards by reducing plant uptake and offsetting the need to apply Cd-contaminated phosphate fertilizers.

Acknowledgments

This research was partially funded by the Centre for Integrated Biowaste Research (CIBR). Shamim Al Mamun acknowledges the receipt of an NZ-AID doctoral scholarship.

References

Al Mamun, S., G. Chanson, Muliadi, E. Benyas, M. Aktar, N. Lehto, R. McDowell, J. Cavanagh, L. Kellermann, L. Clucas, and B. Robinson. 2016. Municipal composts reduce the transfer of Cd from soil to vegetables. Environ. Pollut. 213:8–15. doi:10.1016/j.envpol.2016.01.072

Barkoczi, M., P. Szakal, R. Schmidt, and R. Turi. 2008. Effect of sewage-sludge compost on maize plant. Cereal Res. Commun. 36:1923–1926.

Bernard, A. 2008. Cadmium & its adverse effects on human health. Indian J. Med. Res. 128:557–564.

Bigdeli, M., and M. Seilsepour. 2008. Investigation of metals accumulation in some vegetables irrigated with waste water in Shahre Rey-Iran and toxicological implications. Am-Eurasian J Agric. Environ. Sci. 4:86–92.

Black, A., R.G. McLaren, S.M. Reichman, T.W. Speir, and L.M. Condron. 2012. Examining the integrity of soil metal bioavailability assays in the presence of organic amendments to metal-spiked soils. Soil Use Manage. 28:89–100. doi:10.1111/j.1475-2743.2011.00384.x

Blakemore L.C. 1987. Methods for chemical analysis of soils. NZ Soil Bureau Sci. Report 80:71–76.

Brady, N., and R. Weil. 2008. The nature and properties of soils. Prentice Hall, Upper Saddle River, NJ.

Cadmium Working Group. 2011. Cadmium and New Zealand agriculture and horticulture: A strategy for long term risk management. Ministry of Agriculture and Forestry, Wellington, NZ.

Chaney, R.L., C.E. Green, H.A. Ajwa, and R.F. Smith. 2009. Zinc fertilization plus liming to reduce cadmium uptake by Romaine lettuce on Cd-mineralized Lockwood soil. Proceedings of the International Plant Nutrition Colloquium XVI. Department of Plant Science, UC Davis.

Chen, Y., T. Xie, Q. Liang, M. Liu, M. Zhao, M. Wang, and G. Wang. 2016. Effectiveness of lime and peat applications on cadmium availability in a paddy soil under various moisture regimes. Environ. Sci. Pollut. Res. Int. 23:7757–7766. doi:10.1007/s11356-015-5930-4

Codex. 2011. Working document for information and use in discussions related to contaminants and toxins in the GSCTFF, joint FAO/WHO food standards programme. CODEX Committee on Contaminants in Foods, Codex Alimentarius Commission, The Hague, The Netherlands.

Codex. 2015. Codex Alimentarius International Food Standards, general standard for contaminants and toxins in food and feed (CODEX STAN 193-1995). FAO/WHO.

Corguinha, A.P.B., V.C. Gonçalves, G.A.d. Souza, W.E.A.d. Lima, E.S. Penido, C.A.B.P. Pinto, E.A.B. Francisco, and L.R.G. Guilherme. 2012. Cadmium in potato and soybeans: Do phosphate fertilization and soil management systems play a role? J. Food Compos. Anal. 27:32–37. doi:10.1016/j.jfca.2012.05.001

Covelo, E.F., F.A. Vega, and M.L. Andrade. 2007. Competitive sorption and desorption of heavy metals by individual soil components. J. Hazard. Mater. 140:308–315. doi:10.1016/j.jhazmat.2006.09.018

Dunbar, K.R., M.J. McLaughlin, and R. Reid. 2003. The uptake and partitioning of cadmium in two cultivars of potato (*Solanum tuberosum* L.). J. Exp. Bot. 54:349–354. doi:10.1093/jxb/erg016

Dziubanek, G., A. Piekut, M. Rusin, R. Baranowska, and I. Hajok. 2015. Contamination of food crops grown on soils with elevated heavy metals content. Ecotoxicol. Environ. Saf. 118:183–189. doi:10.1016/j.ecoenv.2015.04.032

EFSA. 2012. European Food Safety Authority, Cadmium dietary exposure in the European population EFSA J. 2012;10(1):2551–2588. doi:10.2903/j.efsa.2012.2551

Fekete, S.G., A. Bersenyi, I. Kádár, R. Glavits, J. Koncz, and L. Zöldág. 2001. Study of soil-plant (potato and beetroot)-animal cycle of nutritive and hazardous minerals in a rabbit model. Acta Vet. Hung. 49:301–310.

Food Standards of Australia and New Zealand (FSANZ). 2015. Australia New Zealand Food Standards Code-Standard 1.4.1: Contaminants and natural toxicants-F2015C00052. FSANZ, Wellington, NZ.

Gray, C.W., R.G. McLaren, A.H.C. Roberts, and L.M. Condron. 1999a. Effect of soil pH on cadmium phytoavailability in some New Zealand soils. N. Z. J. Crop Hortic. Sci. 27:169–179. doi:10.1080/01140671.1999.9514093

Gray, C.W., R.G. McLaren, A.H.C. Roberts, and L.M. Condron. 1999b. Cadmium phytoavailability in some New Zealand soils. Aust. J. Soil Res. 37:461–477. doi:10.1071/S98070

Hart, J.J., R.M. Welch, W.A. Norvell, and L.V. Kochian. 2002. Transport interactions between cadmium and zinc in roots of bread and durum wheat seedlings. Physiol. Plant. 116:73–78. doi:10.1034/j.1399-3054.2002.1160109.x

Hong, C.O., D.K. Lee, D.Y. Chung, and P.J. Kim. 2007. Liming effects on cadmium stabilization in upland soil affected by gold mining activity. Arch. Environ. Contam. Toxicol. 52:496–502. doi:10.1007/s00244-006-0097-0

Hooda, P.S. 2010. Trace elements in soils. Wiley-Blackwell, Chichester, UK

Järup, L., and A. Åkesson. 2009. Current status of cadmium as an environmental health problem. Toxicol. Appl. Pharmacol. 238:201–208. doi:10.1016/j.taap.2009.04.020

Kabata-Pendias, A., and H. Pendias. 2001. Trace elements in soils and plants. CRC Press, Boca Raton, FL.

Kabata-Pendias A., A.B. Mukherjee. 2007. Trace elements from soil to human. Springer, New York.

Khan, M.A.I., K. Ueno, S. Horimoto, F. Komai, K. Tanaka, and Y. Ono. 2007. Evaluation of the physio-chemical and microbial properties of green tea waste-rice bran compost and the effect of the compost on spinach production. Plant Prod. Sci. 10:391–399. doi:10.1626/pps.10.391

Kim, H.S., B.-H. Seo, J.-S. Bae, W.-I. Kim, G. Owens, and K.-R. Kim. 2016. An integrated approach to safer plant production on metal contaminated soils using species selection and chemical immobilization. Ecotoxicol. Environ. Saf. 131:89–95. doi:10.1016/j.ecoenv.2016.05.008

Kim, N. 2008. Cadmium accumulation in Waikato soils, Environment Waikato Regional Council, Hamilton, NZ.

Kovács, B., J. Prokisch, Z. Györi, A.B. Kovács, and A.J. Palencsár. 2000. Studies on soil sample preparation for inductively coupled plasma atomic emission spectrometry analysis. Comm. Soil Sci. Plant Anal. 31:1949–1963.

Krauss, M., and T. Diez. 1997. Uptake of heavy metals by plants from highly contaminated soils. Agribiol. Res. 50:343–349.

Lisinska G., Leszczynski W. (1989) Potato science and technology. Springer Science & Business Media, Berlin, Germany.

Loganathan, P., M.J. Hedley, N. Grace, J. Lee, S. Cronin, N.S. Bolan, and J. Zanders. 2003. Fertiliser contaminants in New Zealand grazed pasture with special reference to cadmium and fluorine: A review. Soil Res. 41:501–532. doi:10.1071/SR02126

MacLean, A.J. 1976. Cadmium in different plant speciesand its availability in soils as influenced by organic matter and additions of lime P, Cd and Zn. Can. J. Soil Sci. 56:129–138. doi:10.4141/cjss76-021

Maier, N., M.J. McLaughlin, M. Heap, M. Butt, and M. Smart. 2002. Effect of nitrogen source and calcitic lime on soil pH and potato yield, leaf chemical composition, and tuber cadmium concentrations. J. Plant Nutr. 25:523–544. doi:10.1081/PLN-120003380

Maier, N.A., M.J. McLaughlin, M. Heap, M. Butt, M.K. Smart, and C.M.J. Williams. 1997. Effect of current-season application of calcitic lime on soil pH, yield and cadmium concentration in potato (*Solanum tuberosum* L.) tubers. Nutr. Cycl. Agroecosyst. 47:29–40. doi:10.1007/BF01985716

McLaughlin, M., C. Williams, A. McKay, R. Kirkham, J. Gunton, K. Jackson, R. Thompson, B. Dowling, D. Partington, M. Smart, and K. Tiller. 1994a. Effect of cultivar on uptake of cadmium by potato tubers. Aust. J. Agric. Res. 45:1483–1495. doi:10.1071/AR9941483

McLaughlin, M.J., L.T. Palmer, K.G. Tiller, T.A. Beech, and M.K. Smart. 1994b. Increased soil salinity causes elevated cadmium concentrations in field-grown potato tubers. J. Environ. Qual. 23:1013–1018. doi:10.2134/jeq1994.00472425002300050023x

McLaughlin, M.J., N.A. Maier, G.E. Rayment, L.A. Sparrow, G. Berg, A. McKay, P. Milham, R.H. Merry, and M.K. Smart. 1997. Cadmium in Australian potato tubers and soils. J. Environ. Qual. 26:1644–1649. doi:10.2134/jeq1997.00472425002600060026x

Merian, E. 1991. Metals and their compounds in the environment: Occurrence, analysis and biological relevance. VCH Verlagsgesellschaft, Weinheim, Germany.

Muhammad, S., T. Mueller, and R.G. Joergensen. 2007. Compost and P amendments for stimulating microorganisms and maize growth in a saline soil from Pakistan in comparison with a nonsaline soil from Germany. J. Plant Nutr. Soil Sci. 170:745–752. doi:10.1002/jpln.200625122

Pandit, T., S. Naik, P. Patra, and D. Das. 2012. Influence of lime and organic matter on the mobility of cadmium in cadmium-contaminated soil in relation to nutrition of spinach. Soil Sediment Contam. 21:419–433.

Pérez, A.L., and K.A. Anderson. 2009. DGT estimates cadmium accumulation in wheat and potato from phosphate fertilizer applications. Sci. Total Environ. 407:5096–5103. doi:10.1016/j.scitotenv.2009.05.045

Peters, J.L., T.S. Perlstein, M.J. Perry, E. McNeely, and J. Weuve. 2010. Cadmium exposure in association with history of stroke and heart failure. Environ. Res. 110:199–206. doi:10.1016/j.envres.2009.12.004

Pusz, A. 2007. Influence of brown coal on limit of phytotoxicity of soils contaminated with heavy metals. J. Hazard. Mater. 149:590–597. doi:10.1016/j.jhazmat.2007.06.115

Rai, S., S. Gupta, and P.C. Mittal. 2015. Dietary intakes and health risk of toxic and essential heavy metals through the food chain in agricultural, industrial, and coal mining areas of northern India. Hum. Ecol. Risk Assess. 21:913–933. doi:10.1080/10807039.2014.946337

Reid, R.J., K.R. Dunbar, and M.J. McLaughlin. 2003. Cadmium loading into potato tubers: The roles of the periderm, xylem and phloem. Plant Cell Environ. 26:201–206. doi:10.1046/j.1365-3040.2003.00945.x

Reiser, R., M. Simmler, D. Portmann, L. Clucas, R. Schulin, and B. Robinson. 2014. Cadmium concentrations in New Zealand pastures: Relationships to soil and climate variables. J. Environ. Qual. 43:917–925. doi:10.2134/jeq2013.09.0367

Roberts, A., R. Longhurst, and M. Brown. 1994. Cadmium status of soils, plants, and grazing animals in New Zealand. N. Z. J. Agric. Res. 37:119–129. doi:10.1080/00288233.1994.9513048

Robinson, B.H., G. Bañuelos, H.M. Conesa, M.W. Evangelou, and R. Schulin. 2009. The phytomanagement of trace elements in soil. Crit. Rev. Plant Sci. 28:240–266. doi:10.1080/07352680903035424

Russell, D., W. Parnell, N. Wilson, J. Faed, E. Ferguson, P. Herbison, C. Horwath, T. Nye, P. Reid, and R. Walker. 1999 NZ food: NZ people. Key results of the 1997 national nutrition survey. Ministry of Health, Wellington, NZ.

Sarwar, G., H. Schmeisky, N. Hussain, S. Muhammad, M. Ibrahim, and E. Safdar. 2008. Improvement of soil physical and chemical properties with compost application in rice-wheat cropping system. Pak. J. Bot. 40:275–282.

Schipper, L.A., G.P. Sparling, L. Fisk, M. Dodd, I. Power, and R.A. Littler. 2011. Rates of accumulation of cadmium and uranium in a New Zealand hill farm soil as a result of long-term use of phosphate fertilizer. Agric. Ecosyst. Environ. 144:95–101. doi:10.1016/j.agee.2011.08.002

Shaheen, S.M., and J. Rinklebe. 2015. Impact of emerging and low cost alternative amendments on the (im) mobilization and phytoavailability of Cd and Pb in a contaminated floodplain soil. Ecol. Eng. 74:319–326. doi:10.1016/j.ecoleng.2014.10.024

Shiralipour, A., D.B. McConnell, and W.H. Smith. 1992. Physical and chemical properties of soils as affected by municipal solid waste compost application. Biomass Bioenergy 3:261–266. doi:10.1016/0961-9534(92)90030-T

Sigel, A., H. Sigel, R.K.O. Sigel, W. Maret, and J.-M. Moulis. 2013. The bioinorganic chemistry of cadmium in the context of its toxicity, cadmium: From toxicity to essentiality. Springer, the Netherlands. doi:10.1007/978-94-007-5179-8

Simmler, M., L. Ciadamidaro, R. Schulin, P. Madejoìn, R. Reiser, L. Clucas, P. Weber, and B. Robinson. 2013. Lignite reduces the solubility and plant uptake of cadmium in pasturelands. Environ. Sci. Technol. 47:4497–4504. doi:10.1021/es303118a

Syers, J.K., A.D. Mackay, M.W. Brown, and L.D. Currie. 1986. Chemical and physical characteristics of phosphate rock materials of varying reactivity. J. Sci. Food Agric. 37:1057–1064. doi:10.1002/jsfa.2740371102

Taylor, M.D. 1997. Accumulation of cadmium derived from fertilisers in New Zealand soils. Sci. Total Environ. 208:123–126. doi:10.1016/S0048-9697(97)00273-8

Taylor M.D., R. Gibb, J. Willoughby, A. Hewitt, and G. Arnold. 2007. Soil maps of cadmium in New Zealand. Ministry of Agriculture and Forestry, Wellington, NZ.

Tiller, K., D. Oliver, M. McLaughlin, R. Merry, R. Naidu, I. Iskander, and D. Adriano. 1997. Managing cadmium contamination of agricultural land: Remediation of soils contaminated with metals. In: Proceedings of a conference on the biogeochemistry of trace elements, Taipei, Taiwan, 5–10 Sept. 1993. Science Reviews Ltd., Northwood, UK. p. 225–255.

Uraguchi, S., S. Mori, M. Kuramata, A. Kawasaki, T. Arao, and S. Ishikawa. 2009. Root-to-shoot Cd translocation via the xylem is the major process determining shoot and grain cadmium accumulation in rice. J. Exp. Bot. 60:2677–2688. doi:10.1093/jxb/erp119

Valentinuzzi, F., T. Mimmo, S. Cesco, S. Al Mamun, J. Santner, C. Hoefer, E. Oburger, B. Robinson, and N. Lehto. 2015. The effect of lime on the rhizosphere processes and elemental uptake of white lupin. Environ. Exp. Bot. doi:10.1016/j.envexpbot.2015.06.010

Weggler-Beaton, K., M.J. McLaughlin, and R.D. Graham. 2000. Salinity increases cadmium uptake by wheat and Swiss chard from soil amended with biosolids. Soil Res. 38:37–46. doi:10.1071/SR99028