Journal of Soil Science and Plant Nutrition (2019) 19:450–462
https://doi.org/10.1007/s42729-019-00050-x

RESEARCH ARTICLE

Fixation Coefficient and Soil Residual Effect of Cadmium Application on Three Biannual Crop Rotations at Four Locations in Chile

Juan Hirzel[1] · Jorge Retamal-Salgado[2] · Ingrid Walter[3] · Iván Matus[1]

Received: 10 April 2018 / Accepted: 7 January 2019 / Published online: 25 April 2019
© Sociedad Chilena de la Ciencia del Suelo 2019

Abstract

Cadmium (Cd) is a metalloid present in agricultural soils and harmful for human health. A large part of the Cd entering into the soil can be fixed, while another portion can contribute to increasing availability indices of this element (residual effect). The present study evaluated Cd residual effect and Cd fixation derived from anthropic applications at four locations in Chile during two seasons. Three crop rotations were used, which included white lupine (*Lupinus albus* L.), narrow-leafed lupine (*Lupinus angustifolius* L.), and durum wheat (*Triticum turgidum* L. var. *durum*) as the first crop and durum wheat as the second crop. Results indicated that the anthropic application of Cd to the soil, in the three crop rotations and at the four locations under study, exhibited a low residual effect in the next season and null effect two seasons after its application. Among the three preceding crops of each rotation, the highest effect on Cd residuality in both seasons was achieved using both lupines, especially narrow-leafed lupine. The Cd fixation coefficient in the upper 0.2 m of soil in the three crop rotations and at the four locations was very high, and it was greater than 99.9% in all cases.

Keywords Soil cadmium fixation · Soil residual cadmium · Crop rotations

1 Introduction

Cadmium (Cd) is one of the most common heavy metal contaminants present in the soil. It is toxic for many living organisms, including some cultivated plants, and is carcinogenic for humans (Bovet et al. 2006; Tsyganov et al. 2007). The Cd concentration that is considered toxic for humans by the World Health Organization (WHO) is a daily intake of 1 μg kg^{-1} body weight (Walker and Herman 2000) or 70 μg Cd per person (Chaudri et al. 1995), which occurs mainly through the ingestion of foods and smoking (Dumbar 2004). In addition, a high Cd concentration in the soil can reduce the uptake of other nutrients as iron, copper, and zinc (Chen et al. 2018).

Heavy metal contamination in crops primarily depends on the following factors: heavy metal concentration in the soil, soil physical-chemical properties, specific toxicity of each heavy metal, differences among species, and plant variety (Lehoczky and Kiss 2006; Grant et al. 2008). Baize et al. (2003) indicated that differences in soil Cd content are mainly due to soil geochemical characteristics. The Cd in the soil is fixed by oxides, hydroxides, clay, and organic matter (OM), and its content can be monitored. In addition, Cd can be fixed in the soil by adsorption from metal ions, association of metal complexes, and slow reactions, such as solid-state diffusion to non-labile metal, which reduce its availability to the plants (Degryse et al. 2009). Sierra et al. (2007) indicate that metals can be fixed by both the inorganic fraction (clay, oxides, and carbonates) and soil OM. Another important complex to estimate Cd bioavailability is chloro-complexation in the soil to enhance Cd uptake by crops through greater Cd diffusion to the roots and soil (McLaughlin et al. 1997).

Many reports for soils of USA, New Zealand, and Hungary had indicated soil total Cd concentrations less than 1 mg kg^{-1} (Holmgren et al. 1993; McDowell et al. 2013; Lehoczky and Kiss 2006), which varied significantly between locations and

✉ Juan Hirzel
jhirzel@inia.cl

[1] Instituto de Investigaciones Agropecuarias, INIA Quilamapu, Avenida Vicente Méndez, 515 Chillán, Chile

[2] Facultad de Ingeniería y Negocios, Universidad Adventista de Chile, km 12 Camino Tanilvoro, Chillán, Chile

[3] Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA), Apdo. Correo 8111, 28080 Madrid, Spain

in some cases were associated to soil properties as different phosphorus (P) fertilization rates and high soil OM content. Normally the values of soil total Cd concentrations higher than 1 mg kg^{-1} had been reported for soils of agriculture urban and peri-urban (Egwu and Agbenin 2013) or from intensive agriculture (Sierra et al. 2007; Buccolieri et al. 2010). For Chilean agricultural soils, González et al. (1997) reported values of total Cd content between 0.19 and < 5.0 mg kg^{-1} in the upper 0.2 m of soil associate to soil genesis and geographic location, and a higher number of samples had values less than 1 mg kg^{-1}.

Major soil factors affecting Cd uptake from the soil to the plants include pH, texture, OM content, total Cd concentration, zinc (Zn), and salinity (McLaughlin et al. 1997). Soil enrichments can lead to the inadvertent and accelerated transfer of trace elements through the food chain (Chen et al. 2008). Additionally, exudation of organic acids, such as citrate (Bovet et al. 2006), malate, and acetate (Han et al. 2006), generate greater plant Cd availability and absorption. Lupine species can exhibit an important Cd uptake by their ability to exude organic acids, for example, narrow-leafed lupine (*Lupineus angustifolius* L.) and white lupine (*Lupinus albus* L.) (Trejo et al. 2016).

Legume crops usually benefit soil properties, however, some species such as white lupine and narrow-leafed lupine, have high Cd uptake and increase soil Cd availability (Trejo et al. 2016). This could affect the Cd uptake in the next crop and be a risk to human health when the next crop exhibits high Cd uptake and translocates this element to the grain, such as durum wheat (*Triticum turgidum* L. var. *durum*) (Hirzel et al. 2017 and 2018a) and corn (Retamal-Salgado et al. 2017).

Given that the crop rotation or the preceding crop and different soil properties could affect soil Cd availability and Cd uptake in the next crop, the objective of this study was to evaluate the residual effect of Cd application to the preceding crop on both total soil Cd concentration and Cd fixation coefficient. The study included three crop rotations of white and narrow-leafed lupine and durum wheat as the preceding and durum wheat as second crop for two consecutive seasons at four agricultural locations in Chile.

2 Materials and Methods

Four field experiments were conducted during the 2013–2014 and 2014–2015 seasons in different agricultural zones of Chile.

2.1 Climatic and Soil Characteristics of each Location

The locations and their climatic characteristics were (i) La Serena (30°3′ S; 71°14′ W), alluvial-colluvial soil (Typic Haplocambids), arid climate, maritime influence, 40 and 127 mm precipitation for the 2013 and 2014 seasons, respectively, concentrated in winter; (ii) Los Tilos (33°34′ S; 70°37′ W), alluvial soil (Haploxeroll), semi-arid and temperate Mediterranean climate with a hot and dry summer and cold winter, 163 and 345 mm precipitation for the 2013 and 2014 seasons, respectively, concentrated in winter; (iii) Chillán (36°31′ S; 71°54′ W), volcanic soil (Melanoxerand), temperate Mediterranean climate with a hot and dry summer and cold and wet winter, 672 and 978 mm precipitation for the 2013 and 2014 seasons, respectively, concentrated in winter and spring; and (iv) Temuco (38°41′ S; 72°25′ W), volcanic soil (Melanudands), Mediterranean climate with a hot and dry summer and cold and rainy winter, 868 and 1284 mm precipitation for the 2013 and 2014 seasons, respectively, concentrated in winter and spring (Red Agrometeorológica de Chile 2013; USDA 2014). The physical-chemical properties at the beginning of the first experimental year for each soil are shown in Table 1.

2.2 Experiment Management

The crop rotations at the four locations were (1) durum wheat-durum wheat, (2) white lupine-durum wheat, and (3) narrow-leafed lupine-durum wheat. Agronomic practices were standarized for all locations and are those normally used in Chile for those crops. For durum wheat, the three cultivars Llareta-INIA, Corcolén-INIA, and Lleuque-INIA were used. They have different genetic backgrounds and were developed by the wheat breeding program of the Institute of Agricultural Research of Chile (Instituto de Investigaciones Agropecuarias, INIA). For white and narrow-leafed lupine, the cultivars were Rumbo and Wonga, respectively.

Each experimental unit was a 15-row plot with 3-m long rows and 0.2-m row spacing (9 m^2). For the first season, experiment sowing dates for both white and narrow-leafed lupine were 15 May 2013 in La Serena and Los Tilos and 17 July 2013 in Chillán and Temuco. Durum wheat were sown on 15 July, 20 July, 20 August, and 25 August 2013 in La Serena, Los Tilos, Chillán, and Temuco, respectively. For the second season (only durum wheat), experiments were sown on 18 July, 25 July, 22 August, and 27 August 2014 in La Serena, Los Tilos, Chillán, and Temuco, respectively. Before the durum wheats were sown, the residues of lupines were removed from the soil surface.

Seed rates were 140 and 120 kg ha^{-1} for white and narrow-leafed lupine, respectively. Irrigation in both lupines were applied in both seasons in La Serena and Los Tilos, at the tillering, pre-flowering, and flowering stages; precipitation during the sowing to flowering period was sufficient for the hydric requirements of the crops in Chillán and Temuco and irrigation was not necessary. In both white and narrow-leafed lupine, fertilization with nitrogen (N) and P were not used because these species do not respond to the application of these

Table 1 Physical-chemical soil properties (0.0–0.2 and 0.2–0.4 m depths) at the four locations under study prior to establishing the first crop of a biannual rotation

Parameters	Locations and depths (cm)							
	La Serena		Los Tilos		Chillán		Temuco	
	0–20	20–40	0–20	20–40	0–20	20–40	0–20	20–40
Clay (%)	20.2	20.3	21.5	27.3	20.7	15.9	25.3	23.1
Silt (%)	30.2	31.2	50.0	49.3	43.6	45.4	38.5	41.5
Sand (%)	49.6	48.5	28.5	23.4	35.7	38.7	36.2	35.4
Bulk density (g cm^{-3})	1.76	1.80	1.20	1.24	1.00	1.05	0.80	0.82
pH $_{(soil:water\ 1:5)}$	6.94	6.87	8.25	8.19	5.74	5.76	5.96	5.92
Organic matter (g kg^{-1})	11.6	11.3	19.6	21.7	63.0	56.2	155.6	143.7
EC (dS m^{-1})	0.15	0.23	0.11	0.15	0.11	0.07	0.09	0.09
Available N (mg kg^{-1})	18.0	20.0	11.0	14.0	40.0	38.0	30.0	28.0
Olsen P (mg kg^{-1})	51.3	44.9	3.9	5.1	35.2	25.3	24.5	20.9
Exchangeable K ($cmol_c$ kg^{-1})	0.85	0.67	0.35	0.41	0.65	0.39	0.67	0.41
Exchangeable Ca ($cmol_c$ kg^{-1})	8.12	8.22	20.70	19.66	6.74	5.89	7.40	7.77
Exchangeable Mg ($cmol_c$ kg^{-1})	2.41	2.61	0.92	0.86	0.95	0.72	0.71	0.76
Exchangeable Na ($cmol_c$ kg^{-1})	0.59	0.69	0.49	0.40	0.16	0.19	0.03	0.05
Exchangeable Al ($cmol_c$ kg^{-1})	0.05	0.05	0.04	0.04	0.21	0.10	0.06	0.05
Available Fe (mg kg^{-1})	21.5	20.8	16.7	17.0	59.8	46.5	55.9	59.9
Available Mn (mg kg^{-1})	36.3	34.3	11.8	11.5	9.8	5.4	3.5	2.8
Available Zn (mg kg^{-1})	4.5	4.4	1.1	1.2	0.7	0.6	0.8	0.6
Available Cu (mg kg^{-1})	9.2	9.3	8.9	8.8	1.4	1.2	1.0	0.9
Available B (mg kg^{-1})	2.3	2.4	0.8	0.8	0.5	0.4	0.3	0.3
Available S (mg kg^{-1})	40.8	64.9	11.9	13.5	14.2	15.4	14.6	9.6
Total Cd (mg kg^{-1})	1.33	1.49	0.52	0.51	0.21	0.18	0.14	0.14

EC electrical conductivity, *N* nitrogen, *P* phosphorus, *K* potassium, *Ca* calcium, *Mg* magnesium, *Na* sodium, *Al* aluminum, *Fe* iron, *Mn* manganese, *Zn* zinc, *Cu* copper, *B* boron, *S* sulfur, *Cd* cadmium

elements. Soil available potassium (K) was sufficient for crop needs (Table 1).

In both seasons, 220 kg seed ha^{-1} of durum wheat was used for each cultivar. Irrigation was applied at tillering (La Serena and Los Tilos), booting stage, heading, and milk-to-dough stage (all locations) according to crop demand so as not to generate any restriction. Total weed control was carried out and disease control was not necessary. The N, P, and K fertilization rates for durum wheat in both seasons were 240, 120, and 120 kg ha^{-1}, respectively, and fertilizer sources were urea, triple superphosphate, and potassium chloride. Nitrogen was applied 15%, 45%, and 40% at sowing, tillering, and flag leaf, respectively. Both P and K were applied 100% at sowing.

At the beginning of the first season (crop preceding the second crop to be evaluated in the present experiment), Cd was applied as $CdCl_2$ (61.3% Cd) at rates of 0, 1, and 2 mg kg^{-1} adjusted for the 0–0.2 m soil depth and taking into account the apparent density of each soil (Table 1). The equivalent amount of Cd applied at rates of 1 and 2 mg kg^{-1} $CdCl_2$ at each location was (i) La Serena 2157.76 and 4315.52 g ha^{-1}, respectively; (ii) Los Tilos 1593.8 and 3187.6 g ha^{-1}, respectively; (iii) Chillán 1226.0 and 2452.0 g ha^{-1}, respectively; and (iv) Temuco 980.8 and 1916.6 g ha^{-1}, respectively. The application of $CdCl_2$ was performed in a solution with distilled water at the rate of 20 mL m^{-2}. Cadmium was not applied in the second season.

2.3 Grain Yield, Plant Tissue, and Soil Analysis

Plots were harvested manually at maturity and the whole plot yield was expressed as t ha^{-1}. Plant samples of 1.0 m^2 were collected at harvest time in each experimental unit at each location. Grain and tissue samples were oven-dried at 70 °C for 72 h. To determine Cd content in plant tissues, dried samples were ground with a mill and passed through a 2 mm sieve. Tissue samples were digested with nitric acid concentrate (in a microwave), and Cd in the solution was determined by inductively coupled plasma-optical emission spectrometry (ICP-OES). Both Cd concentration and extraction in plant tissues of white and narrow-leafed lupine (first season of two of the three crop rotations) were reported by Trejo et al. (2016) and by Hirzel et al. (2017 and 2018b) for the first season of durum wheat (one of the three crop rotations). The Cd concentration

and extraction in plant tissues of durum wheat in the second season of the three crop rotations were reported by Hirzel et al. (2018b).

Chemical soil analysis was performed before starting the experiment using the next methodology; soil pH was measured in a 1:2.5 soil:water ratio solution with a pH meter. Soil OM was measured by the Walkley-Black wet digestion method. Soil available N (NO_3-N and NH_4-N) was extracted with 2 M KCl and determined by colorimetry in an auto-analyzer (segmented flux spectrophotometer; Skalar, Breda, The Netherlands). Available P was determined by 0.5 M $NaHCO_3$ (Olsen P) using the ascorbic acid–molybdate method. Exchangeable calcium (Ca), Mg, K, and sodium (Na) were determined by 1 M NH_4OAc extraction followed by flame spectroscopy, absorption (Ca and Mg), and emission (K and Na). Soil exchangeable aluminum (Al) concentration was determined with 1 M KCl extraction by absorption spectroscopy. The iron (Fe), Mn, Zn, and copper (Cu) concentrations in soils were determined in diethylenetriaminepentaacetic acid (DTPA) extract by atomic absorption spectrometry (AAS). Boron was determined by colorimetry in a solution obtained by acid digestion. Sulfur (SO_4^{2-}) was determined with calcium phosphate 0.01 M and turbidimetry. Total soil Cd was determined by extraction with HNO_3-HCl (aqua regia) and analyzed by ICP-OES (Table 1). The reference material used for Cd plant analysis was Acacia (leaf)/Robina pseudo IPE 999–Wepal. The reference material for Cd soil analysis Metals in Soil SQC001–Anab/Sigma Aldrich.

Total soil Cd was determined at two depths, 0–0.2 and 0.2–0.4 m, at the end of each crop harvest (2014 and 2015) using ten replicates by experimental unit, which allowed determining the residual effect of the $CdCl_2$ applications at the beginning of each crop rotation (2013).

The Cd fixation coefficient was determined using Eqs. 1 to 6.

$$\textit{Cd extraction compared to control}\ \left(g\ ha^{-1}\right) = \textit{Cd extraction}\ (\textit{treatment–control})\ \left(g\ ha^{-1}\right) \quad (1)$$

$$\text{Soil Cd net input} = \left(\text{Cd rate applied at beginning of rotation}^{\text{i}}\text{–Cd extraction control}^{\text{ii}}\right)\ \left(\text{g ha}^{-1}\right) \quad (2)$$

[i]Cd applied at rates of 1 and 2 mg kg^{-1} $CdCl_2$ expressed in g ha^{-1} was adjusted to bulk density of each location (0.0–0.2 m); respective values were 2157.76 and 4315.52 g ha^{-1} in La Serena, 1593.8 and 3187.6 g ha^{-1} in Los Tilos, 1226.0 and 2452.0 g ha^{-1} in Chillán, and 980.8 and 1916.6 g ha^{-1} in Temuco.

[ii]Cd extraction compared to control is the difference between Cd extraction of treatment with 1 or 2 mg kg^{-1} $CdCl_2$ and the control without Cd application. For the second season, extractions of both the first and second crops of each rotation were considered.

$$\text{Soil Cd net input}\ \left(\text{mg kg}^{-1}\right) = \left(\text{Soil Cd net input}\ \left(\text{g ha}^{-1}\right)\right) / \left(\text{bulk density}\ \left(\text{g cm}^{-3}\right)^{*}\ 2^{\text{iii}}\right) \quad (3)$$

[iii]2 is the factor that allows correcting the soil mass in which $CdCl_2$ is applied at the 0.0–0.2 m depth.

$$\text{Soil Cd increase compared to control}_{(0.0\text{–}0.2\ \text{m})} = \text{Total soil Cd concentration (treatment–control)}\ \left(\text{mg kg}^{-1}\right) \quad (4)$$

$$\textit{Relationship between soil Cd increase compared to Cd net input}\ (\%) = \frac{(\textit{Soil Cd increase compared to control})\ (\textit{mg kg}^{-1})^{*}}{(\textit{Soil Cd net input})\ (\textit{mg kg}^{-1})}\ 100 \quad (5)$$

$$\text{Cd fixation} = (100\text{–Relationship between soil Cd increase compared to Cd net input}\ (\%))\ \text{coefficient}\ (\%) \quad (6)$$

2.4 Experimental Design and Statistical Analysis

The experimental design was a split-split-split plot in which the main plot was the location (4), the split plot was the crop rotation, the split-split plot was the Cd rate (3), and the split-split-split plot was the durum wheat cultivar (3) with three replicates.

Results were analyzed by ANOVA and Tukey's test ($P = 0.05$) by the SAS PROC MIXED Model procedure (SAS Institute, Cary, North Carolina, USA 1989), and locations were considered as non-random effects. For the significant interactions, contrast analysis was used to separately compare the treatment effects.

3 Results

3.1 Significance Analysis

The soil residual Cd concentration exhibited significant differences among locations ($p < 0.01$) in both seasons and soil depths (Table 2). There was a location × crop interaction in the first season and second soil stratum (Table 2); results are found in Table 3. There also occurred an interaction location × Cd rate × durum wheat cultivar in the second season in both soil strata; results are shown in Tables 4 and 5 for the first and second soil stratums, respectively. Interactions were also obtained at the 0.0–0.2 m and 0.2–0.4 m depth for the 2014 season as an effect of the Crop rotation × $CdCl_2$ rate interaction (Table 6). The analysis of results as pull date for locations, crop rotations, $CdCl_2$ rates, and durum wheat cvs., comparing between soil depth in each season is presented in the Table 7.

Table 2 Significance analysis for soil total cadmium (Cd) concentration

Variation source	2014 season		2015 season	
	0.0–0.2 m	0.2–0.4 m	0.0–0.2 m	0.2–0.4 m
Location (L)	**	**	**	**
Crop rotation (CR)	**	**	**	ns
Cd rate (Cd)	**	ns	ns	ns
Durum wheat cultivar (W)	*	**	**	ns
L × CR	ns	**	ns	ns
L × Cd	ns	ns	ns	ns
L × W	ns	ns	ns	ns
CR × Cd	**	*	ns	ns
CR × W	ns	ns	ns	ns
Cd × W	ns	ns	**	ns
L × CR × Cd	ns	ns	ns	ns
L × CR × W	ns	ns	ns	ns
L × Cd × W	ns	ns	**	**
CR × Cd × W	ns	ns	ns	ns
L × CR × Cd × W	ns	ns	ns	ns

L (4): La Serena, Los Tilos, Chillán, Temuco; CR (3): DW (durum wheat)-DW, WL (white lupine)-DW, NL (narrow-leafed lupine)-DW; Cd rate (3); 0, 1, and 2 mg kg^{-1} $CdCl_2$; W: Llareta-INIA, Corcolen-INIA, and Lleuque-INIA

In the first season (2013–2014), the highest soil Cd concentration in the upper 0.2 m of soil was obtained in La Serena ($p < 0.05$), with no differences among other locations ($p > 0.05$, Table 7). When comparing soil depths at the same location (Table 7), there were differences in La Serena, Chillán, and Temuco ($p < 0.05$), and the highest Cd concentration was always obtained at the surface (0–0.2 m).

3.2 Soil Total Cd Concentration as Effect of the Location × Crop Rotation Interaction

When comparing locations for the location × crop rotation interaction in the second season at the 0.2–0.4 m soil depth ($p < 0.01$; Table 2), La Serena achieved the highest Cd concentration in the rotations initiated by both lupines ($p < 0.05$), with no differences between them ($p > 0.05$; Table 3). The highest Cd concentration in Los Tilos was obtained in the rotation initiated by narrow-leafed lupine, which only surpassed the value obtained by the durum wheat monoculture ($p < 0.05$; Table 3). There were no differences between crop rotations in Chillán ($p > 0.05$; Table 3). In Temuco, the highest soil Cd concentration was attained in the rotation initiated by narrow-leafed lupine ($p < 0.05$), with no differences with the other two rotations ($p > 0.05$; Table 3). When comparing crop rotations, the durum wheat monoculture had the highest Cd concentration in La Serena ($p < 0.05$), followed by Los Tilos

Table 3 Soil total cadmium concentration at the 0.2–0.4 m depth for the 2014 season as an effect of the Location × Crop rotation interaction

Location	Crop rotation			Location mean value
	DW-DW	WL-DW	NL-DW	
La Serena	0.757 Ba	1.174 Aa	1.412 Aa	1.114 a
Los Tilos	0.548 Bb	0.644 ABb	0.688 Ab	0.627 b
Chillán	0.337 Ac	0.485 Ab	0.363 Ac	0.395 c
Temuco	0.334 Bc	0.439 Bb	0.565 Abc	0.446 c
Crop rotation mean value	0.494 B	0.685 AB	0.757 A	

DW durum wheat (means of cvs. Llareta-INIA, Corcolen-INIA, and Lleuque-INIA), *WL* white lupine, *NL* narrow-leafed lupine

Different uppercase letters in the same row indicate differences between crop rotations according to Tukey's test ($p < 0.05$)

Different lowercase letters in the same column indicate differences between locations according to Tukey's test ($p < 0.05$)

Table 4 Soil total cadmium concentration at 0.0–0.2 m depth for the 2015 season as an effect of the Location × $CdCl_2$ rate × durum wheat cultivar interaction

Location	$CdCl_2$ rate (mg kg soil^{-1})	Durum wheat cultivar			$CdCl_2$ rate mean value
		Llareta	Corcolen	Lleuque	
La Serena	0	0.661 Cb	1.497 Ba	2.534 Aa	1.564 a
	1	0.900 Cb	1.948 Aa	1.677 Bb	1.509 a
	2	1.966 Aa	0.748 Bb	1.142 Bb	1.286 a
	Durum wheat cultivar mean value	1.176 B	1.398 AB	1.785 A	
Los Tilos	0	0.503 Ab	0.698 A a	0.622 Aa	0.608 a
	1	0.558 Bb	0.762 Aa	0.701 ABa	0.674 a
	2	0.767 Aa	0.408 Bb	0.569 ABa	0.581a
	Durum wheat cultivar mean value	0.609 A	0.623 A	0.631 A	
Chillán	0	0.250 Cb	0.507 Ba	0.875 Aa	0.544 a
	1	0.352 Bb	0.717 Aa	0.502 Bb	0.524 a
	2	0.789 Aa	0.270 Bb	0.464 Bb	0.508 a
	Durum wheat cultivar mean value	0.464 A	0.498 A	0.614 A	
Temuco	0	0.284 Cb	0.831 Bb	1.327 Aa	0.814 a
	1	0.326 Cb	1.161 Aa	0.701 Bb	0.729 a
	2	1.227 Aa	0.365 Bc	0.655 Bb	0.749 a
	Durum wheat cultivar mean value	0.612 A	0.786 A	0.894 A	

For each location, different uppercase letters in the same row indicate differences between durum wheat cultivars according to Tukey's test ($p < 0.05$)

For each location, different lowercase letters in the same column indicate differences between $CdCl_2$ rates according to Tukey's test ($p < 0.05$)

($p < 0.05$), and with no differences between Chillán and Temuco ($p > 0.05$; Table 3). When white lupine initiated the rotation, the highest soil Cd concentration was achieved in La Serena ($p < 0.05$), with no differences among the other locations ($p > 0.05$; Table 3). The rotation initiated by narrow-leafed lupine had the highest Cd concentration in La Serena ($p < 0.05$), followed by Los Tilos ($p < 0.05$), and the lowest value was found in Chillán ($p < 0.05$); there were no differences between Chillán and Temuco ($p > 0.05$) and between Los Tilos and Temuco ($p > 0.05$; Table 3). All soil Cd values were usually lower at 1 mg kg^{-1}, except in La Serena with rotations initiated by both lupines.

3.3 Soil Total Cd Concentration at 0.0–0.2 m Depth as Effect of the Location × $CdCl_2$ Rate × Durum Wheat Cultivar Interaction in La Serena Location

Erratic effects were exhibited between cultivars at different $CdCl_2$ rates used at the beginning of each rotation in the location × Cd rate × durum wheat cultivar interaction ($p < 0.01$; Table 2) in the second season, 0–0.2 m stratum (Table 4). The highest Cd concentration in the control without Cd was obtained in cv. Lleuque-INIA ($p < 0.05$), followed by cv. Corcolén-INIA, whose value was greater than cv. Llareta-INIA ($p < 0.05$; Table 4). The highest Cd concentration value for the 1 mg kg^{-1} $CdCl_2$ rate occurred in cv. Corcolén-INIA ($p < 0.05$; Table 4). The 2 mg kg^{-1} $CdCl_2$ rate used at the beginning of the rotation had the highest Cd concentration value in cv. Llareta-INIA ($p < 0.05$; Table 4). When comparing the different Cd rates used in the same durum wheat cultivar, it was observed that Llareta-INIA exhibited the highest Cd concentration value at the highest rate applied at the beginning of the rotation ($p < 0.05$) and with no differences between the other rates ($p > 0.05$; Table 4). The cv. Corcolén-INIA showed the highest Cd concentration values at the lowest Cd rate applied at the beginning of the rotation ($p < 0.05$; Table 4). The highest soil Cd concentration for cv. Lleuque-INIA was obtained in the control with no Cd application ($p < 0.05$; Table 4).

3.4 Soil Total Cd Concentration at 0.0–0.2 m Depth as Effect of the Location × $CdCl_2$ Rate × Durum Wheat Cultivar Interaction in Los Tilos Location

Erratic effects also occurred in Los Tilos between cultivars at the different Cd rates used at the beginning of the rotation (Table 4). The control without Cd did not exhibit any differences in soil Cd concentration between cultivars ($p > 0.05$). The 1-mg-kg^{-1} $CdCl_2$ rate attained the highest Cd concentration value in cv. Corcolén-INIA ($p < 0.05$) and only surpassed

Table 5 Soil total cadmium concentration at the 0.2–0.4 m depth for the 2015 season as an effect of the Location × $CdCl_2$ rate × durum wheat cultivar interaction

Location	$CdCl_2$ rate (mg kg soil^{-1})	Durum wheat cultivar			$CdCl_2$ rate mean value
		Llareta	Corcolen	Lleuque	
La Serena	0	0.605 Cb	0.914 Bb	1.220 Aa	0.913 a
	1	0.895 Bab	1.306 Aa	1.055 ABab	1.085 a
	2	1.282 Aa	0.655 Bb	0.716 Bb	0.884 a
	Durum wheat cultivar mean value	0.927 A	0.958 A	0.997 A	
Los Tilos	0	0.457 Aab	0.537 Aa	0.473 Aa	0.489 a
	1	0.390 Bb	0.554 Aa	0.536 ABa	0.493 a
	2	0.629 Aa	0.409 ABa	0.372 Ba	0.470 a
	Durum wheat cultivar mean value	0.492 A	0.500 A	0.460 A	
Chillán	0	0.225 Cb	0.373 Ba	0.489 Aa	0.362 a
	1	0.327 Aab	0.447 Aa	0.337 Ab	0.371 a
	2	0.393 Aa	0.213 Bb	0.317 Ab	0.308 a
	Durum wheat cultivar mean value	0.315 A	0.345 A	0.381 A	
Temuco	0	0.272 Cb	0.755 Ba	1.060 Aa	0.696 a
	1	0.326 Cb	0.893 Aa	0.644 Bb	0.621 a
	2	0.986 Aa	0.346 Cb	0.625 Bb	0.652 a
	Durum wheat cultivar mean value	0.528 B	0.665 AB	0.777 A	

For each location, different uppercase letters in the same row indicate differences between durum wheat cultivars according to Tukey's test ($p < 0.05$)

For each location, different lowercase letters in the same column indicate differences between $CdCl_2$ rates according to Tukey's test ($p < 0.05$)

cv. Llareta-INIA ($p < 0.05$; Table 4). The 2-mg-kg^{-1} $CdCl_2$ rate led to the highest Cd concentration value in cv. Llareta-INIA ($p < 0.05$) and only surpassed cv. Corcolén-INIA ($p < 0.05$; Table 4). When comparing the $CdCl_2$ rates used at the beginning of the rotation in the same durum wheat cultivar, there was no difference in cv. Lleuque-INIA ($p > 0.05$). The highest Cd concentration value in cv. Llareta-INIA was achieved at the highest Cd rate ($p < 0.05$), whereas the highest

Table 6 Soil total cadmium concentration at the 0.0–0.2 m and 0.2–0.4 m depth for the 2014 season as an effect of the Crop rotation × $CdCl_2$ rate interaction

$CdCl_2$ rate (mg kg soil^{-1})	Crop rotation			$CdCl_2$ rate mean value
	DW-DW	WL-DW	NL-DW	
Depth 0.0–0.2 m				
0	0.337 Cc	0.726 Ba	0.963 Aa	0.675 b
1	0.625 Bb	0.827 Aa	0.972 Aa	0.808 ab
2	1.029 Aa	0.875 Aa	0.877 Aa	0.927 a
Crop rotation mean value	0.664 B	0.809 AB	0.937 A	
Depth 0.2–0.4 m				
0	0.316 Bc	0.722 Aa	0.712 Aa	0.583 a
1	0.466 Bb	0.708 Aa	0.776 Aa	0.650 a
2	0.700 Aa	0.627 Aa	0.782 Aa	0.703 a
Crop rotation mean value	0.494 B	0.685 AB	0.757 A	

DW durum wheat (mean of cvs. Llareta-INIA, Corcolen-INIA, and Lleuque-INIA), *WL* white lupine, *NL* narrow-leafed lupine

Different uppercase letters in the same row indicate differences between crop rotations according to Tukey's test ($p < 0.05$)

Different lowercase letters in the same column indicate differences between $CdCl_2$ rates according to Tukey's test ($p < 0.05$)

Table 7 Soil total cadmium (Cd) concentration at two depths (0–0.2 m and 0.2–0.4 m) at four Chilean locations, three biannual crop rotations, three $CdCl_2$ rates applied at beginning of a biannual crop rotation, and three durum wheat cvs. (Llareta-INIA, Corcolén-INIA, and Lleuque-INIA) presented as average of pull dates, after harvesting the first crop of a biannual rotation (2014 season) and after harvesting the second crop of a biannual rotation (2015 season)

	Season 2014		Season 2015	
Location	*0.0–0.2 m*	*0.2–0.4 m*	*0.0–0.2 m*	*0.2–0.4 m*
La Serena	1.319 Aa	1.114 Ab	1.453 Aa	0.961 Ab
Los Tilos	0.629 Ba	0.627 Ba	0.621 BCa	0.484 Cb
Chillán	0.598 Ba	0.395 Cb	0.525 Ca	0.347 Db
Temuco	0.669 Ba	0.446 Cb	0.764 Ba	0.656 Bb
Crop rotation	*0.0–0.2 m*	*0.2–0.4 m*	*0.0–0.2 m*	*0.2–0.4 m*
DW-DW	0.664 Ba	0.494 Bb	0.720 Ba	0.573 Ab
WL-DW	0.809 ABa	0.685 ABb	0.921 Aa	0.652 Ab
NL-DW	0.937 Aa	0.757 Ab	0.882 Aa	0.612 Ab
$CdCl_2$ rate (mg kg^{-1})	*0.0–0.2 m*	*0.2–0.4 m*	*0.0–0.2 m*	*0.2–0.4 m*
0	0.675 Ba	0.583 Ab	0.882 Aa	0.615 Ab
1	0.808 ABa	0.650 Ab	0.859 Aa	0.643 Ab
2	0.927 Aa	0.703 Ab	0.781 Aa	0.579 Ab
Durum wheat cultivars	*0.0–0.2 m*	*0.2–0.4 m*	*0.0–0.2 m*	*0.2–0.4 m*
Llareta-INIA	0.776 Ba	0.583 Bb	0.715 Ba	0.566 Ab
Corcolén-INIA	0.786 Ba	0.664 Ab	0.826 ABa	0.617 Ab
Lleuque-INIA	0.849 Aa	0.689 Ab	0.981 Aa	0.654 Ab

DW durum wheat (mean of cvs. Llareta-INIA, Corcolen-INIA, and Lleuque-INIA), *WL* white lupine, *NL* narrow-leafed lupine

Different uppercase letters in the same row for the same season indicate differences according to Tukey's test ($p < 0.05$)

Different lowercase letters in the same column for the same season indicate differences according to Tukey's test ($p < 0.05$)

Cd concentration values in cv. Corcolén-INIA were obtained with the two lower Cd rates ($p < 0.05$; Table 4).

3.5 Soil Total Cd Concentration at 0.0–0.2 m Depth as Effect of the Location × $CdCl_2$ Rate × Durum Wheat Cultivar Interaction in Chillán and Temuco Location

The effects observed in $CdCl_2$ rate × durum wheat cultivar interactions in Chillán and Temuco were similar to those described for La Serena (Table 4); there were differences between cultivars at the 1-mg-kg^{-1} $CdCl_2$ rate in Chillán where the highest soil Cd concentration was found in cv. Corcolén-INIA ($p < 0.05$), with no differences between the other cultivars ($p > 0.05$).

3.6 Soil Total Cd Concentration at 0.2–0.4 m Depth as Effect of the Location × $CdCl_2$ Rate × Durum Wheat Cultivar Interaction in La Serena Location

There were erratic effects between cultivars at the different $CdCl_2$ rates applied at the beginning of each rotation. The highest Cd concentration in the control without Cd was obtained in cv. Lleuque-INIA ($p < 0.05$), followed by cv. Corcolén-INIA, whose value surpassed cv. Llareta-INIA ($p < 0.05$; Table 5). At the 1-mg-kg^{-1} $CdCl_2$ rate, the highest soil Cd concentration value was obtained in cv. Corcolén-INIA, whose value only surpassed cv. Llareta-INIA ($p < 0.05$; Table 5). For the 2-mg-kg^{-1} $CdCl_2$ rate the highest Cd concentration value was obtained in cv. Llareta-INIA ($p < 0.05$; Table 5). When comparing the different Cd rates used in the same durum wheat cultivar, cv. Llareta-INIA exhibited the highest Cd concentration value at the highest rate applied at the beginning of the rotation, and this value only surpassed the control ($p < 0.05$; Table 5). The cv. Corcolén-INIA had the highest Cd concentration value at the 1-mg-kg^{-1} $CdCl_2$ rate used at the beginning of the rotation ($p < 0.05$; Table 5). The highest soil Cd concentration in cv. Lleuque-INIA took place in the control with no Cd application, and its value only surpassed the value obtained at the highest Cd rate applied at the beginning of the rotation ($p < 0.05$; Table 5). It should be noted that four of the durum wheat cv.× $CdCl_2$ rate interactions in La Serena surpassed the 1-mg-kg^{-1} total Cd value.

3.7 Soil Total Cd Concentration at 0.2–0.4 m Depth as Effect of the Location × $CdCl_2$ Rate × Durum Wheat Cultivar Interaction in Los Tilos Location

Erratic effects also occurred between cultivars at different Cd rates applied at the beginning of the rotation (Table 5). There were no differences in soil Cd concentration between cultivars ($p > 0.05$) in the control without Cd. The highest Cd concentration value was reached in cv. Corcolén-INIA ($p < 0.05$) at

the 1-mg-kg^{-1} $CdCl_2$ rate; it only exceeded the value in cv. Llareta-INIA (Table 5). At the 2-mg-kg^{-1} $CdCl_2$ rate, the highest Cd concentration value was attained in cv. Llareta-INIA, which only surpassed cv. Lleuque-INIA ($p < 0.05$; Table 5). When comparing the $CdCl_2$ rates used at the beginning of the rotation in the same durum wheat cultivar, the only difference occurred in cv. Llareta-INIA, and the highest Cd concentration value was achieved at the highest $CdCl_2$ rate applied at the beginning of the rotation ($p < 0.05$), which only surpassed the value obtained at the 1-mg-kg^{-1} rate (Table 5).

3.8 Soil Total Cd Concentration at 0.2–0.4 m Depth as Effect of the Location × $CdCl_2$ Rate × Durum Wheat Cultivar Interaction in Chillán Location

There were also erratic effects between cultivars at the different $CdCl_2$ rates used at the beginning of each rotation. The control without Cd recorded the highest Cd concentration value in cv. Lleuque-INIA, followed by cv. Corcolén-INIA, whose value was superior to cv. Llareta-INIA ($p < 0.05$; Table 5). There were no differences in soil Cd concentration between cultivars at the 1-mg-kg^{-1} $CdCl_2$ rate ($p > 0.05$; Table 5). For the 2-mg-kg^{-1} $CdCl_2$ rate applied at the beginning of the rotation, the highest Cd concentration value was achieved in cvs. Llareta-INIA and Lleuque-INIA ($p < 0.05$; Table 5). When comparing the different Cd rates applied in the same durum wheat cultivar, it was observed that the highest Cd concentration value in cv. Llareta-INIA was reached at the highest rate applied at the beginning of the rotation ($p < 0.05$), and its value only outperformed the control ($p < 0.05$; Table 5). The cv. Corcolén-INIA reached its highest Cd concentration value at the two lowest $CdCl_2$ rates applied at the beginning of the rotation ($p < 0.05$), with no differences between them ($p > 0.05$; Table 5). The cv. Lleuque-INIA achieved the highest soil Cd concentration in the control without Cd application ($p < 0.05$; Table 5).

3.9 Soil Total Cd Concentration at 0.2–0.4 m Depth as Effect of the Location × $CdCl_2$ Rate × Durum Wheat Cultivar Interaction in Temuco Location

The effects of the durum wheat cultivar × $CdCl_2$ rate interaction on the soil Cd concentration in Temuco were similar to those described for Chillán (Table 5) and with only a few exceptions. The highest Cd concentration value at the 1-mg-kg^{-1} $CdCl_2$ rate occurred in cv. Corcolén-INIA ($p < 0.05$), followed by cv. Lleuque-INIA, whose value surpassed cv. Llareta-INIA ($p < 0.05$; Table 5). At the 2-mg-kg^{-1} $CdCl_2$ rate, the highest Cd concentration value was obtained in cv. Llareta-INIA ($p < 0.05$), followed by cv. Lleuque-INIA, whose value was superior to cv. Corcolén-INIA ($p < 0.05$; Table 5). The cv. Llareta-INIA reached the highest soil Cd concentration at the highest $CdCl_2$ rate applied ($p < 0.05$; Table 5). The cv. Lleuque-INIA × control without Cd interaction at this location generated total soil Cd concentration greater than 1 mg kg^{-1}.

3.10 Soil Total Cd Concentration at 0.0–0.2 and 0.2–0.4 m Depth as Effect of the Crop Rotation × $CdCl_2$ Rate Interaction

In addition to the interaction between crop rotations and the location mentioned above for the first season (Table 3), the crop rotation exhibited an interaction with the Cd rate in the first season in both soil stratum (Table 2); results appear in Tables 6 for the first and second soil stratum, respectively. The highest Cd concentration in the 0–0.2 m soil stratum for the control without Cd took place in the rotation initiated with narrow-leafed lupine ($p < 0.05$), followed by the rotation initiated with white lupine ($p < 0.05$), whose value was higher than the durum wheat monoculture ($p < 0.05$; Table 6). For the 1-mg-kg^{-1} $CdCl_2$ rate, the highest Cd concentration values were obtained in both rotations initiated by lupines ($p < 0.05$; Table 6). There were no differences in Cd concentration between crop rotations at the highest $CdCl_2$ rate ($p > 0.05$; Table 6). When comparing crop rotations in the upper soil stratum (0–0.2 m), there was only a difference in the durum wheat monoculture ($p < 0.05$; Table 6), and the soil Cd concentration relationship was directly proportional to the $CdCl_2$ rate applied at the beginning of the rotation.

In the 0.2–0.4 m soil stratum (Table 6) and for the control without Cd and for the 1-mg-kg^{-1} $CdCl_2$ rate, the highest Cd concentration was found in the rotations initiated by both lupines ($p < 0.05$). There were no differences in soil Cd concentration between rotations at the highest $CdCl_2$ rate ($p > 0.05$; Table 6). When comparing the Cd rate in the same rotation, a difference was observed only in the durum wheat monoculture ($p < 0.05$; Table 6), whose soil Cd concentration was directly proportional to the Cd rate used at the beginning of the rotation.

3.11 Soil Total Cd Concentration at 0.0–0.2 and 0.2–0.4 m Depth as Mean of Locations, Crop Rotations, $CdCl_2$ Rates, and Durum Wheat Cultivars

In the first season, only the Cd concentration in the first soil stratum (0–0.2 m) in La Serena exceeded the maximum concentration of 1 mg kg^{-1} indicated by Lehoczky and Kiss (2006) (Table 7). In the second season (2014–2015) and at all locations, the Cd concentration was higher at the surface (0–0.2 m) soil depth ($p < 0.05$; Table 7), and no value exceeded the 1-mg-kg^{-1} concentration.

When comparing soil depths for the same crop rotation in both seasons (Table 7), there were differences in all rotations ($p < 0.05$); the highest Cd concentration was always obtained on the surface (0–0.2 m) and did not exceed the 1-mg-kg^{-1}

concentration. Comparing between crop rotations, for the first season the higher value in the 0–0.2 m soil stratum was obtained with narrow-leafed lupine as preceding crop ($p < 0.05$) (Table 7), while that in the second seasons, the highest Cd concentration occurred in the white lupine-durum wheat and narrow-leafed lupine-durum wheat rotations ($p < 0.05$) (Table 7).

The $CdCl_2$ rate effect in the first season (Table 7) at the 0–0.2 m depth was higher with the rate of 2 mg kg^{-1} $CdCl_2$, which only surpassed only the control with no Cd application ($p < 0.05$). When comparing soil depths at the same Cd rate (Table 7), there were differences at all $CdCl_2$ rates ($p < 0.05$), and the highest Cd concentration was always achieved on the surface (0–0.2 m) without exceeding the 1-mg-kg^{-1} concentration. There were differences in the second season (2015) between soil depths (Table 7) for the same $CdCl_2$ rate ($p < 0.05$), and the highest value was obtained in the upper soil stratum.

When the effect of the durum wheat cultivar on the soil total Cd concentration was evaluated, the highest value at the 0–0.2-m stratum in the first season was obtained in cv. Lleuque-INIA ($p < 0.05$) without differences between the other cultivars ($p > 0.05$; Table 7). For the second soil stratum (0.2–0.4 m), the highest total Cd concentration occurred in cvs. Lleuque-INIA and Corcolén-INIA ($p < 0.05$; Table 7). When comparing the stratum for the same cultivar (Table 7), the Cd concentration was always higher in the upper soil stratum ($p < 0.05$), and no value surpassed the 1-mg-kg^{-1} concentration. The highest soil total Cd concentration in the upper soil stratum (0–0.2 m) in the second season (2015) was found in cv. Lleuque-INIA ($p < 0.05$), which only surpassed cv. Llareta-INIA (Table 7). When comparing stratum in the same cultivar (Table 7), the highest Cd concentration was reached in the upper soil stratum ($p < 0.05$) and values were less than 1 mg kg^{-1}.

3.12 Soil Cadmium Fixation Coefficient

The Cd extraction values in lupines and durum wheat crops (Table 8) were discussed previously by Trejo et al. (2016) and Hirzel et al. (2017 and 2018a), and they were normal for lupines and low to normal for the durum wheat cultivars. The soil residual Cd concentration (Table 8) was very low at both applied $CdCl_2$ rates, and the increase compared to the control was mainly observed in the same application season (2014), generating a low percentage increase and high soil Cd fixation rate. The Cd fixation coefficient obtained (Table 8) at the four locations fluctuated between 99.92 and 100% for the 2014 season and between 99.98 and 100% for the 2015 season. Mean Cd fixation for the 2014 season (both $CdCl_2$ rates) was 99.97% and 100% for the 2015 season. The mean Cd fixation value (2014 and 2015) at both $CdCl_2$ rates was 99.98% (Table 8). When crop rotations were compared, the mean values obtained at both $CdCl_2$ rates and seasons were 99.97%, 99.99%, and 99.99% for durum wheat-durum wheat, white lupine-durum wheat, and narrow-leafed lupine-durum wheat, respectively (Table 8). These values indicate very high Cd fixation, which was similar at all locations (fluctuating from 99.98 to 99.99% as the mean of both $CdCl_2$ rates and seasons; Table 8), although soils had different physical-chemical properties.

4 Discussion

The effects of each location on the differences in the residual Cd concentration (Table 2, Table 7) are associated with the physical-chemical properties (Table 1) and genesis of each soil, as indicated by several authors (Baize et al. 2003; Fang et al. 2013; McDowell et al. 2013). Holmgren et al. (1993) reported differences in Cd concentration in 2771 samples of agricultural soils in different states of the USA associated with different P fertilization rates and high soil OM content. McDowell et al. (2013) also indicate a high correlation between soil total Cd and total P concentrations. A similar effect described above is only observed at the La Serena location (Table 1) (the highest total Cd and available P concentrations); however, the highest Cd concentration observed at this location can be related primarily to soil genesis (sedimentary soil with considerable content of both salts and metals) (Luzio 2010) in which a higher Cd concentration has been reported (Baize et al. 2003; McDowell et al. 2013). McDowell et al. (2013) point out that the main natural source of soil Cd is the weathering of parent materials rich in sulfides, such as the soils in northern Chile (La Serena location, Table 1). Overall, a total Cd concentration greater than 1 mg kg^{-1} was only observed at the La Serena location; Lehoczky and Kiss (2006) reported that this concentration is critical. It is associated with the initial Cd content of this soil (Table 1), which can be generated mainly by soil genesis and meteorization factors (Baize et al. 2003; McDowell et al. 2013).

Differences in Cd concentration between locations at different soil depths (Table 1), such as those detected with a significant effect in the present study (Table 2, Table 7), have been reported by Egwu and Agbenin (2013) for agricultural soils in Nigeria. Regarding anthropogenic contamination of Cd in the soil, low mobility towards deeper soil stratum have been reported for fixation processes associated with physical-chemical properties, such as clay, oxide, carbonate, and OM content (Christensen and Haung 1999; Sierra et al. 2007).

Crop rotation exhibited significant effects on soil Cd concentration in most situations (Table 2, Table 7). Oliver et al. (1993) indicate that the Cd concentration in wheat grain was

Table 8 Cadmium (Cd) balance and soil fixation coefficient at the 0.0–0.2 m depth for the 2014 and 2015 seasons in three biannual crop rotations with Cd applications at the beginning of the first crop at the La Serena, Los Tilos, Chillán, and Temuco locations

Season	Crop rotation	Balance components	La Serena		Los Tilos		Chillán		Temuco	
			$CdCl_2$ rates (mg kg^{-1})							
			1	2	1	2	1	2	1	2
2014	DW-DW	Cd extraction	22.30	24.12	5.11	10.22	8.48	13.96	3.03	5.10
		Cd input^{i}	2135.5	4291.4	1588.7	3177.4	1217.5	2438.0	977.8	1956.5
		Cd input^{ii}	606.7	1219.1	611.0	1222.1	608.8	1219.0	611.1	1222.8
		Soil Cd increase^{i}	0.49	0.82	0.15	0.30	0.26	1.00	0.25	0.65
		Soil Cd increase^{ii}	0.082	0.067	0.024	0.024	0.043	0.082	0.040	0.053
		Cd fixation	**99.92**	**99.93**	**99.98**	**99.98**	**99.96**	**99.92**	**99.96**	**99.95**
	WL-DW	Cd extraction	450.5	899.6	24.8	68.1	656.0	930.8	123.7	266.2
		Cd input^{i}	1707.3	3415.9	1569.0	3119.5	570.0	1521.2	857.1	1695.4
		Cd input^{ii}	485.0	970.4	603.5	1199.8	285.0	760.6	535.7	1059.7
		Soil Cd increase^{i}	0.19	0.14	0.09	0.00	0.00	0.40	0.13	0.05
		Soil Cd increase^{ii}	0.039	0.014	0.015	0.00	0.00	0.053	0.024	0.005
		Cd fixation	**99.96**	**99.99**	**99.99**	**100.0**	**100.0**	**99.95**	**99.98**	**100.0**
	NL-DW	Cd extraction	1156.7	3773.4	129.2	259.6	643.6	1142.3	515.5	753.2
		Cd input^{i}	1001.1	542.1	1464.6	2928.0	582.4	1309.7	465.3	1208.4
		Cd input^{ii}	284.4	154.0	563.3	1126.2	291.2	654.8	290.8	755.2
		Soil Cd increase^{i}	0.00	0.11	0.19	0.00	0.00	0.00	0.00	0.00
		Soil Cd increase^{ii}	0.00	0.071	0.034	0.00	0.00	0.00	0.00	0.00
		Cd fixation	**100.0**	**99.93**	**99.97**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**
2015	DW-DW	Cd extraction	10.34	11.27	2.13	4.46	2.05	3.53	1.06	1.63
		Cd input^{i}	2125.1	4280.1	1586.6	3172.9	1215.5	2434.5	976.7	1954.9
		Cd input^{ii}	603.7	1215.9	610.2	1220.4	607.7	1217.3	610.4	1221.8
		Soil Cd increase^{i}	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.00
		Soil Cd increase^{ii}	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
		Cd fixation	**100.0**	**100.0**	**100.0**	**100.0**	**99.99**	**100.0**	**100.0**	**100.0**
	WL-DW	Cd extraction	0.95	2.68	0.21	0.57	1.36	2.6	0.87	1.05
		Cd input^{i}	1706.3	3413.2	1568.8	3118.9	568.7	1518.6	856.2	1694.4
		Cd input^{ii}	484.7	969.7	603.4	1199.6	284.3	759.3	535.2	1059.0
		Soil Cd increase^{i}	0.06	0.00	0.11	0.00	0.00	0.00	0.00	0.04
		Soil Cd increase^{ii}	0.01	0.00	0.02	0.00	0.00	0.00	0.00	0.00
		Cd fixation	**99.99**	**100.0**	**99.98**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**
	NL-DW	Cd extraction	4.94	12.46	0.26	1.39	1.86	4.18	0.92	2.19
		Cd input^{i}	996.1	529.6	1464.4	2926.6	580.5	1305.5	464.4	1206.2
		Cd input^{ii}	283.0	150.5	563.2	1125.6	290.2	652.7	290.2	753.9
		Soil Cd increase^{i}	0.00	0.00	0.14	0.04	0.01	0.05	0.00	0.00
		Soil Cd increase^{ii}	0.00	0.00	0.02	0.00	0.00	0.01	0.00	0.00
		Cd fixation	**100.0**	**100.0**	**99.98**	**100.0**	**100.0**	**99.99**	**100.0**	**100.0**

DW durum wheat (mean of cvs. Llareta-INIA, Corcolen-INIA, and Lleuque-INIA), *WL* white lupine, *NL* narrow-leafed lupine, *Cd extraction* Cd accumulated extraction compared to control (g ha^{-1}) in 2014 and 2015, *Cd input^{i}* soil net residual Cd input (g ha^{-1}), for the 2015 season, the Cd accumulated extraction compared to the control (2014 and 2015) was considered, *Cd input^{ii}* soil net residual Cd input (mg kg^{-1}), *Soil Cd increase^{i}* soil Cd increase compared to the control (mg kg^{-1}), *Soil Cd increase^{ii}* relationship between soil Cd increase with respect to net residual Cd input (%), *Cd fixation* Cd fixation coefficient (%)

The bold underline the Cd fixation

higher when grown after lupines than in other rotations, similar to that showed for the Cd extraction in this study (Trejo et al. 2016; Hirzel et al. 2018a), and associated with the solubilization capacity of Cd in lupine roots (Bovet et al. 2006; Han et al. 2006; Trejo et al. 2016). However, those authors do not mention any effects on the soil Cd

concentration. The effects of crop rotation on the Cd concentration in durum wheat grain have also been reported by Gao and Grant (2012), who compared (i) wheat/flax (*Linum usitatissimum* L.)/durum wheat and (ii) canola (*Brassica napus* L.)/flax/durum wheat rotations. These authors reported differences in only one of three seasons and for one of the two evaluated locations; there was a higher Cd concentration in durum wheat grain when the preceding crops were canola/flax. However, they did not report effects on the total soil Cd concentration. When comparing locations for the same rotation, it was observed that the highest Cd concentration was usually in La Serena (Table 3); causes were previously discussed and associated to soil genesis. The effects noted in the Cd concentration after the narrow-leafed and white lupine (season 2014) concur with Cd concentration results in wheat grain indicated by Oliver (1993). Mean total Cd concentration values did not exceed the 1-mg-kg^{-1} critical value in any of the cases (Lehoczky and Kiss 2006).

The effect observed by the Cd rate applied at the beginning of each rotation was only detected in the first season (2014) in the upper soil stratum (0–0.2 m) (Table 2, Table 7), and there was a directly proportional relationship with the applied anthropogenic rate. This effect had been described by Holmgren et al. (1993) and is associated with Cd entry through the applied phosphate fertilizer rate. The absence of differences between Cd rates in the second soil stratum in the first season (2014) and in both soil stratum in the second season (2015) (Table 2, Table 7) can be associated with soil Cd fixation factors mentioned above (Christensen and Haung 1999; Sierra et al. 2007). To respect is necessary underline the soil properties as the high OM in Temuco and Chillán locations, high pH in La Serena and Los Tilos locations, both high Ca content in Los Tilos and the Zn content in La Serena locations, as factors that allow explain both the high soil Cd fixation and the low effect on the soil Cd increase derived from anthropic applications.

Differences in the effects of the durum wheat cultivar on soil residual Cd concentration (Table 2, Table 7) have not been reported in other studies; however, Grant et al. (2008) have described differences among durum wheat cultivars for the Cd concentration in durum wheat grains. Hirzel et al. (2018a) reported differences in grain Cd concentration in three durum wheat cultivars used in their experiment; cv. Lleuque-INIA had a lower concentration as well as lower Cd extraction in the plant. This lower Cd extraction by cv. Lleuque-INIA can explain the higher residual Cd concentration found in the upper soil stratum (0–0.2 m) (Table 7), although it only differed from cv. Corcolén-INIA in the first season (2014).

The location × $CdCl_2$ rate × durum wheat cultivar interactions at the first (0–0.2 m) and second soil stratum (0.2–0.4 m) in the second season (2015) (Tables 4 and 5, respectively), generally showed higher quantitative differences in soil Cd concentration in La Serena and Temuco, and with a higher effect of cv. Lleuque-INIA, especially in the upper soil stratum in La Serena (Table 4) and in the second soil stratum in Temuco (Table 5). The $CdCl_2$ rates applied at the beginning of each rotation (2014) exhibited very erratic effects and a slight or null increase in soil Cd concentration (Tables 4 and 5), which is due to previously described soil fixation factors (Christensen and Haung 1999; Sierra et al. 2007).

Regarding the Cd balance and soil Cd fixation (Table 8), the increase in Cd concentration values compared to the control were very low at all locations and seasons; they were associated with soil Cd fixation factors (Christensen and Haung 1999; Sierra et al. 2007). Fixation values exhibited in Table 8 were therefore very high and with no quantitative differences among locations, which show minor effects of the different physical-chemical properties of each soil. To respect, Sánchez et al. (2011) indicated that there was a high degree of Cd adsorption in four agricultural soils in Venezuela with contrasting properties and differences among soils, and it was related to texture properties, pH, effective cation exchange capacity (ECEC), and Ca and OM contents. Rábago (2011) indicates 100% and more than 75% Cd sorption in Spain in limestone and non-limestone soils, respectively. Accordingly, the results obtained in the present study indicate that at least 99.9% of anthropogenically applied Cd was fixed in the soil. Considering those results, probably a best indicator of the soil Cd mobilization or fixation could be the Cd available or bio-available, which was not determined in this study.

5 Conclusions

The anthropic application of cadmium (Cd) to the soil at different rates in three crop rotations and at the four locations under study showed a slight residual effect in the next season and a null effect two seasons after its application.

Of the three cultivars preceding each rotation, the highest effect on Cd residuality in both evaluation seasons was achieved using both lupines and narrow-leafed lupine was always highlighted. As for the durum wheat cultivar used in the second season, it had a higher overall effect on soil Cd residuality with cv. Lleuque-INIA, which exhibited an interaction with location and applied $CdCl_2$ rate.

The Cd fixation coefficient in the upper 0.2 m of soil in the three crop rotations and at the four locations under study was very high and exceeded 99.9% in all cases.

Funding Information This study was funded by the Fondo Nacional de Desarrollo Científico y Tecnológico (FONDECYT) Project 1120992, Chile.

References

Baize D, Mench M, Sappin-Didier V (2003) Phytodisponibilité des elements traces métalliques dans les grains de blé. Dossier de l'Environnement de l'INRA 25:45–62

Bovet L, Rossi L, Lugon-Moulin N (2006) Cadmium partitioning and gene expression studies in *Nicotiana tabacum* and *Nicotiana rustica*. Physiol Plant 128:466–477

Buccolieri A, Buccolieri G, Dell'Atti A, Strisciullo G, Gagliano-Candela R (2010) Monitoring of total and bioavailable heavy metals concentration in agricultural soils. Environ Monit Assess 168:547–560

Chaudri AM, Zhao FJ, McGrath SP, Crosland AR (1995) The cadmium content of British wheat grain. J Environ Qual 24:850–855

Chen W, Krage N, Wu L (2008) Arsenic, cadmium, and lead in California cropland soils: role of phosphate and micronutrients fertilizers. J Environ Qual 37:689–695

Chen W, Dong Y, Hu G, Bai X (2018) Effects of exogenous nitric oxide in cadmium toxicity and antioxidative system in perennial ryegrass. J Soil Sci Plant Nutr 18:129–143

Christensen, T.H. and P.M. Haung. 1999. Solid phase cadmium and the reactions of aqueous cadmium with soil surfaces. In 'Cadmium in soils and plants'. (eds. MJ McLaughlin, BR Singh) pp. 65–96. (Springer Science+Business Media, BV)

Degryse F, Smolders E, Parker DR (2009) Partitioning of metals (Cd, Co, Cu, Ni, Pb, Zn) in soils: concepts, methodologies, prediction and applications – a review. Eur J Soil Sci 60:590–612

Dumbar K (2004) Uptake and partitioning of cadmium in two cultivars of potato (*Solanum tuberosum* L.) (PhD thesis University of Adelaide, School of earth and environmental science)

Egwu G, Agbenin J (2013) Field assesment of cadmium, lead and zinc contamination of soils and leaf vegetables under urban and peri-urban agricultura in northern Nigeria. Arch Agron Soil Sci 59: 875–887

Fang S, F, Hua Wang F, Wang X, He W, Wen D, Feng Wang Q, Xiang Liu X (2013) Soil threshold values of total and available cadmium for vegetable growing based on field data in Guangdong province, South China. J Sci Food Agric 93:1967–1973

Gao X, Grant CA (2012) Cadmium and zinc concentration in grain of durum wheat in relation to phosphorus fertilization, crop sequence and tillage management. App Environ Soil Sci 10:1–10

González S, Ite R and Gálvez X (1997) Heavy metal profiles in Chilean agricultural soils: a transect from the III region of Atacama to the XI region of Aysén. In 'Fourth International Conference on the Biogeometry of Trace Elements. Extended abstracts' (Eds IK Iskandar, SE hardy, AC Chang, GM Pierzynski). pp.43-44. (Berkeley, California. USA)

Grant CA, Clarke JM, Duguid S, Chaney RL (2008) Selection and breeding of plant cultivars to minimize cadmium accumulation. Sci Total Environ 390:301–310

Han F, Shan X, Zhang S, Wen B, Owens G (2006) Enhanced cadmium accumulation in maize roots-the impact of organic acids. Plant Soil 289:355–368

Hirzel J, Retamal-Salgado J, Walter I, Matus I (2017) Cadmium accumulation and distribution in plants of three durum wheat cultivars under different agricultural environments in Chile. J Soil Water Conserv 72(1):77–88. https://doi.org/10.2489/jswc.72.1.77

Hirzel J, Retamal-Salgado J, Walter I, Matus I (2018a) Effect of soil cadmium concentration on three Chilean durum wheat cultivars in four environments. Arch Agron Soil Sci 64:162–172. https://doi.org/10.1080/03650340.2017.1337892

Hirzel J, Retamal-Salgado J, Walter I, and Matus I (2018b) Residual effect of cadmium applications in different crop rotations and environments on durum wheat cadmium accumulation. J Soil Water Conserv 74:41–50. https://doi.org/10.2489/jswc.74.1.41

Holmgren G, Meyer M, Chaney R, Daniels R (1993) Cadmium, lead, zinc, cooper and niquel in agricultural soils of the United States of America. J Environ Qual 22:335–348

Lehoczky É, Kiss Z (2006) Study of the transfer coefficient of cadmium and lead in ryegrass and lettuce. Commun Soil Sci Plant Anal 37: 2531–2539

Luzio W (2010) Suelos de Chile (Departamento de Ingeniería y Suelos. Facultad de Ciencias Agronómicas. Universidad de Chile: Santiago)

McDowell RW, Taylor MD, Stevenson BA (2013) Natural background and anthropogenic contributions of cadmium to New Zealand soils. Agric Ecosyst Environ 165:80–87

McLaughlin MJ, Tiller KG, Smart K (1997) Speciation of cadmium in soil solutions of saline/sodic soils and relationship with cadmium concentrations in potato tubers (*Solanum tuberosum* L.). Aust J Soil Res 35:183–198

Oliver DP, Shultz JE, Tiller KG, Merry RH (1993) The effect of crop rotations and tillage practices on cadmium concentration in wheat grain. Aust J Agric Res 44:1221–1234

Rábago I (2011) Capacidad de amortiguación de la contaminación por plomo y por cadmio en suelos de la comunidad de Madrid. Tesis doctoral. Universidad Complutense de Madrid, p 2013

Red Agrometeorológica de Chile (2013) [On line] Available: http://agromet.inia.cl/estaciones.php. Accessed 26 Jan 2015

Retamal-Salgado J, Walter I, Matus I, Hirzel J (2017) Absorption and distribution of cadmium of three maize hybrids in three environments. J Soil Sci Plant Nutr 17(2):266–278

Sánchez N, Subero N, Rivero YC (2011) Determination of the adsorption of cadmium by adsorption isotherms in agricultural soils venezuelans. Acta Agron 60:190–197

SAS Institute. 1989. Usage and reference. Version 6. SAS Institute Inc., Cary, North Carolina, USA

Sierra M, Martínez FJ, Aguilar J (2007) Baselines for trace elements and evaluation of environmental risk in soils of Almería (SE Spain). Geoderma 139:209–219

Trejo N, Matus I, Del Pozo A, Walter I, Hirzel J (2016) Cadmium phytoextraction capacity of white lupine (*Lupineus albus* L.) and narrow-leafed lupine (*Lupineus angustifolius* L.) in three contrasting agroclimatic conditions of Chile. Chil J Agric Res 76:228–235

Tsyganov V, Belimov A, Borisov A, Safronova V, Georgi M, Dietz K, Tikhonovich I (2007) A chemically induced new pea (*Pisum sativum*) mutant SHEETt with increased tolerance and accumulation of cadmium. Ann Bot 99:227–237

United States Department of Agriculture (USDA) (2014) Keys to soil taxonomy. 12th ed. 360 p. Washington DC: USDA

Walker R and Herman JL (2000) Summary and conclusions of a joint FAO/WHO expert committee on food additives. Report 55. World Health Organization: Geneva. http://www.who.int/pcs/jecfa/

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.