J Arid Land
doi: 10.1007/s40333-013-0194-7
jal.xjegi.com; www.springer.com/40333

Interaction between Cd and Pb in the soil-plant system: a case study of an arid oasis soil-cole system

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Abstract: The Hexi Corridor, our study area, is located in Northwest China and is also the most developed area of oasis farming in arid regions of Northwestern China. However, the rapid development of metallurgy and chemical industries in this region poses a great threat to the accumulation of heavy metals in crops. The objectives of this study are (1) to determine the influence of heavy metals on plant growth; (2) to assess the translocation capability of heavy metals in soil-plant system; and (3) to investigate the interaction between heavy metals. Pot experiments were conducted on cole (*Brassica campestris* L.) grown in the arid oasis soils singly and jointly treated with cadmium (Cd) and lead (Pb). Nine treatments were applied into the pots. Under the same planting conditions, three scenarios of Cd, Pb and Cd–Pb were designed to compare the interaction between Cd and Pb. The results showed that the response of cole weights to Cd, Pb and Cd–Pb treatments was slight, while Cd and Pb uptakes in cole were more sensitive to the single effects of Cd and Pb concentration in soils from the lower treatment levels. Under the influence of the single Cd, Pb and joint Cd–Pb treatments, Cd concentrations were lower in the cole roots than in the shoots, while for Pb, the results were opposite. Comparison studies revealed that the interaction of Cd and Pb could weaken the cole's ability to uptake, concentrate and translocate heavy metals in arid oasis soils.

Keywords: heavy metals; interaction; vegetables; oasis soils; arid regions; *Brassica campestris* L.

Citation: ZhuanJun ZHAO, ZhongRen NAN, ZhaoWei WANG, YiMing YANG, Masayuki SHIMIZU. 2013. Interaction between Cd and Pb in the soil-plant system: a case study of an arid oasis soil-cole system. Journal of Arid Land, doi: 10.1007/s40333-013-0194-7.

Recently, the safety issues of agro-products caused by heavy metal pollutants have attracted considerable global attention. Long-term sewage irrigation, fertilizer use, and piled-up industrial solid waste are the primary causes for metallic elements' accumulation in the surface layer of agricultural soils (Devkota and Schmidt, 2000; Singh et al., 2005; Sridhara et al., 2007). Heavy metals, such as Cd, Pb, Cr and As, which have a long soil retention time (Kumar et al., 1995), may transfer and accumulate in the bodies of animals or human beings throughout the food chain, and will probably cause serious threats to human, animals, and ecosystem health (McIntyre, 2003). To improve human health, more information about heavy metals' uptake and transport within agro-products is necessary.

The Hexi Corridor is the most developed area of oasis farming in the arid region of Northwestern China (Jiao et al., 2003). In this area, the development of secondary industries, such as the metallurgy and chemical industries, has greatly improved the local economy while also having a distinctly adverse impact on the environment (Ding et al., 2008). Improper land-use and soil management were strong influencing factors in the accumulation of heavy metals in crops (Su and Yang, 2008).

The accumulation and transfer of heavy metals are usually controlled by soil physical and chemical properties, plant species, and the interaction between heavy metals (McBride, 2003). In reality, heavy metal

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Received 2012-12-12; revised 2013-03-11; accepted 2013-04-05

pollutants often co-exist in soil and plant system. Much evidence on the behavior of multiple heavy metals has been published. However, no unanimous conclusions can be drawn. Some combined pollution experiments indicate that the interaction of heavy metals which lie in the same columns of the periodic table were antagonistic because they had very similar properties, and metals in the same row were superimposed because of competitive adsorption (Zong and Ding, 2001). Other researches indicate that the associated effect of multiple heavy metals on vegetables was caused by competitive adsorption, complexation-chelation and changing enzymatic activity (Li et al., 2002; Guo and Zhou, 2003).

The present study aims to compare the accumulation properties of Cd and Pb (a compound contamination that exists in most urban soils throughout China). These two heavy metals were added separately or in combination in an arid oasis soil-cole system. Under the same planting conditions, the difference of three designed scenarios of Cd, Pb, and Cd–Pb could reveal the characteristics of interaction between Cd and Pb in the system.

1 Materials and methods

1.1 Pot experiments

The oasis soil samples for the pot experiments were collected from a non-polluted site in Linze of Zhangye city, in the Hexi Corridor of Northwestern China. The background concentrations of Cd and Pb in this region were 0.1 and 20.4 mg/kg, respectively. The values of pH, Cation Exchange Capacity (CEC), $CaCO_3$ and soil organic matter, which were measured by the methods of pH meter method, ammonium acetate method, gasometric method, and potassium chromate oxidation method, were 8.2, 8.1 cmol/kg, 13.9%, and 1.5%, respectively. The soil used was silt sandy irrigation soil, collected from the top 20 cm of soil, then air-dried and passed through a 2-mm sieve to remove stones and plant debris. Nine treatments (Table 1) were replicated three times to minimize experimental deviation. The Cd and Pb were added by spraying a solution of each metal nitrate salts over dry soils spread out on a large tray. The soils, weighting 3 kg each, were filled into plastic pots with enough water to 60% of field capacity. Four cole (*Brassica campestris* L.) seeds were transplanted into each pot. All processes of experimentation were conducted under open-air conditions. After 90 days, the harvested cole samples were divided into roots and shoots, which were then carefully rinsed and washed with deionized water, dried at 105°C for 20 minutes, and then at 70°C for 12 hours in an oven until completely dried. The dried cole samples were weighed, ground to powder, and passed through 60-mesh sieves for heavy metal analysis. Soil samples were also air-dried, ground with a mortar and pestle, and passed through a 100-mesh sieve. Fifty grams of soil were selected for analysis through cone quartering.

Table 1 Three scenarios of Cd and Pb in oasis soil

Scenarios	TS0	TS1	TS2	TS3	TS4	TS5	TS6	TS7	TS8
	(mg/kg)								
Cd	0	0.35	0.70	1.05	1.40	2.10	3.50	4.90	7.00
Pb	0	75	150	225	300	450	750	1,050	1,500
Cd+Pb	0, 0	0.35, 75	0.70, 150	1.05, 225	1.40, 300	2.10, 450	3.50,750	4.90, 1,050	7.00, 1,500

1.2 Heavy metal analysis in cole

The cole samples were digested by HNO_3-$HClO_4$ based on the guideline in GB/T5009 (Lu, 1999). Heavy metal concentrations were determined by GF-AAS (Thermo Electron; Type M6 MKII). In the course of determination, we used certified reference materials for quality assurance. Reagent blanks and internal standards were used to ensure accuracy and precision of Cd and Pb analysis. Data were statistically processed using Microsoft Excel and SPSS 13.0. The values were expressed as mean±standard deviations of the three replicates. Data were analyzed by one-way ANOVA with the Duncan's multiple range tests and paired T-test to separate means.

2 Results

2.1 Weight response to Cd, Pb and Cd–Pb treatments

As can be seen from Table 2, the weights of the three scenarios averaged 0.40–1.08, 0.21–0.96, and 0.51–1.42 g/pot for roots, and 13.77–27.56, 9.51–30.77, and 14.98–21.09 g/pot for shoots, respectively. Compared to the mean value of the control (TS0), treated cole showed a maximum increase of about 25% ($P>0.05$) and a maximum decrease of –53% ($P>0.05$; minus represents decrease) in underground weights for Cd stress, 12% ($P>0.05$) and –76% for Pb stress, and 65% ($P>0.05$) and –40% ($P>0.05$) for Cd–Pb stress, respectively; with respect to aboveground weights, the percentages were approximately 29% ($P>0.05$) and –36% for Cd stress, 44% ($P>0.05$) and –56% for Pb stress, and –30% (there was no increased amount) for Cd–Pb stress. However, most of the values showed no significant difference ($P>0.05$) when compared within the same column or same row, indicating that the weight response to Cd, Pb and Cd–Pb treatments was slight.

2.2 Impact of Cd and Pb interaction on heavy metal uptake in cole

2.2.1 Impact of Cd treatment on Cd uptake in different tissues of cole

The concentrations of Cd in cole roots and shoots under Cd treatment are provided in Fig. 1. The results showed that Cd uptake in cole roots and shoots increased with the increment of Cd treatment level. Cd concentrations in the roots and shoots in the control (TS0) were significantly ($P<0.05$) higher than those in TS3 (Cd: 1.05 mg/kg) and TS2 (Cd: 0.70) treatments respectively. The results suggested that Cd uptake in the cole was sensitive to the effects of Cd concentration in soils from the lower treatment levels. Under the influence of the Cd treatment, Cd concentration in the cole roots was lower than that in the shoots.

2.2.2 Impact of Pb treatment on Pb uptake in different tissues of cole

The results of Pb uptake in cole tissues showed that with the increment of Pb treatment level, Pb uptake in roots and shoots increased (Fig. 1). Pb concentrations in both roots and shoots in the control (TS0) were significantly ($P<0.05$) higher than that in TS1 (Pb: 75 mg/kg) treatment. It was also found that cole was sensitive to the toxicological effects of Pb from lower treatment levels. Compared in roots, Pb uptake in shoots varied much more smoothly with the variation of treatment level. Under the influence of Pb toxicity, Pb concentration was higher in the cole roots than in the shoots.

2.2.3 Impact of Cd–Pb treatment on Cd and Pb uptake in different tissues of cole

As shown in Fig. 1, the concentrations of the two

Table 2 Effects of Cd and Pb stress on the fresh weights of cole shoots and roots

Treatment level	Root fresh weight (g)			Shoot fresh weight (g)		
	Cd treatment	Pb treatment	Cd–Pb treatment	Cd treatment	Pb treatment	Cd–Pb treatment
TS0	0.86 ± 0.12^{ab}	0.86 ± 0.12^{cd}	0.86 ± 0.12^{ab}	21.43 ± 3.24^{bcd}	21.43 ± 3.24^{bc}	21.43 ± 3.24^{b}
TS1	0.59 ± 0.13^{abA}	0.42 ± 0.31^{abA}	1.42 ± 1.02^{bB}	14.38 ± 1.95^{abA}	14.41 ± 4.86^{abA}	19.20 ± 2.01^{abA}
TS2	0.49 ± 0.07^{abA}	0.62 ± 0.29^{bcdA}	0.72 ± 0.18^{aA}	13.77 ± 3.16^{aA}	20.69 ± 6.67^{bA}	15.07 ± 1.12^{aA}
TS3	0.55 ± 0.03^{abA}	$0.96\pm0.14^{d\,B}$	0.84 ± 0.30^{abAB}	15.68 ± 2.08^{abA}	30.77 ± 8.08^{cB}	21.09 ± 0.90^{bA}
TS4	0.40 ± 0.31^{aA}	0.40 ± 0.06^{abA}	0.52 ± 0.11^{aA}	17.09 ± 1.5^{abA}	21.48 ± 2.72^{bcA}	16.21 ± 3.14^{aA}
TS5	1.08 ± 0.53^{bB}	0.56 ± 0.07^{bcA}	0.65 ± 0.09^{aA}	27.56 ± 6.04^{dA}	18.21 ± 2.68^{abA}	18.03 ± 1.78^{abA}
TS6	1.07 ± 0.48^{bA}	0.65 ± 0.19^{bcdA}	0.51 ± 0.15^{aA}	21.11 ± 3.22^{bcdB}	23.05 ± 6.72^{bcAB}	14.98 ± 2.45^{aA}
TS7	0.73 ± 0.19^{abA}	0.44 ± 0.18^{abA}	0.59 ± 0.05^{aA}	17.68 ± 5.75^{abcA}	14.97 ± 5.26^{abA}	17.05 ± 3.21^{abA}
TS8	0.87 ± 0.40^{abB}	0.21 ± 0.05^{aA}	0.54 ± 0.13^{aB}	$24.36\pm4.4\ 7^{cdB}$	9.51 ± 2.55^{aA}	17.94 ± 2.18^{abB}

Note: Different lowercase letters within the same column and different uppercase letters within the same row indicate significant differences at $P<0.05$ level according to the Duncan's test.

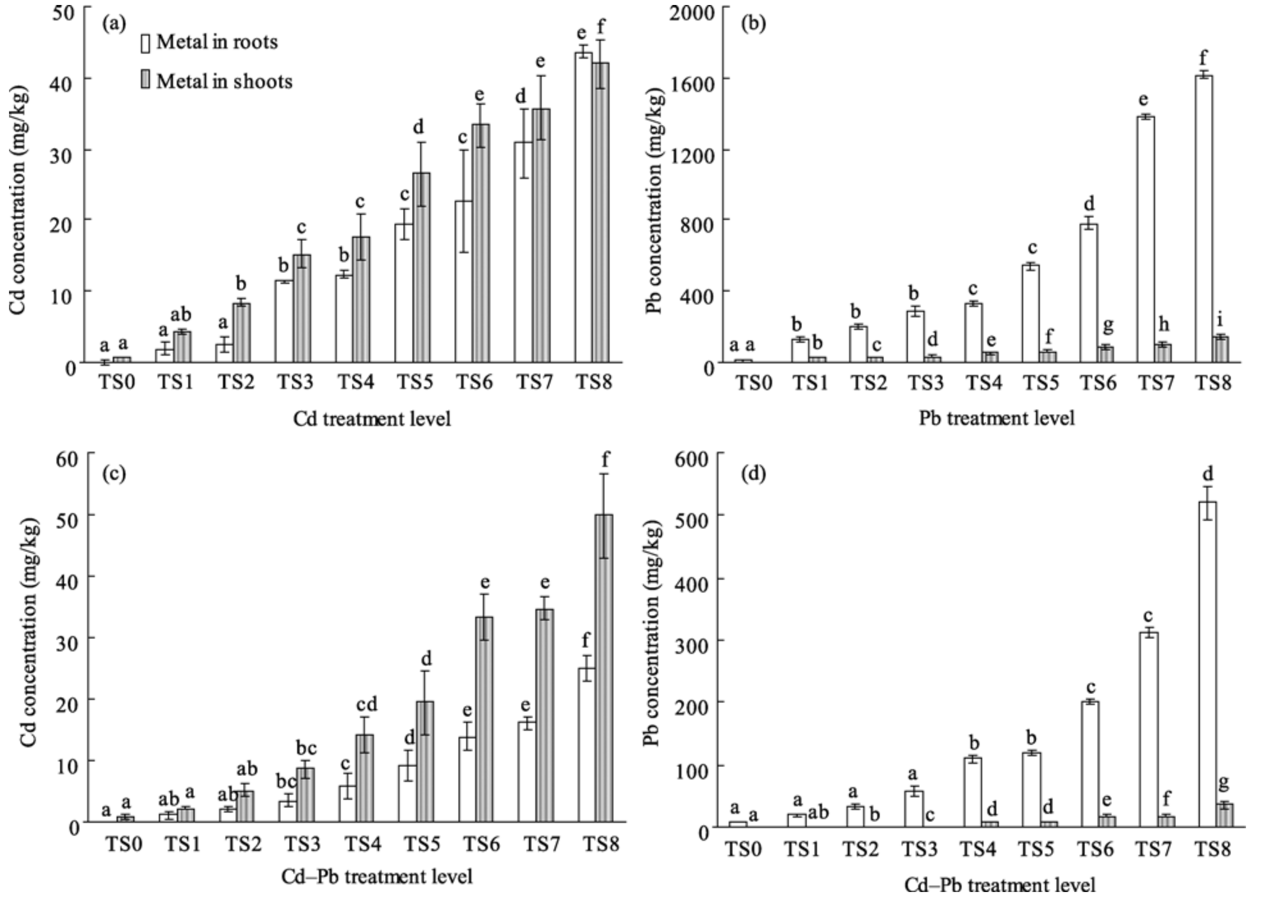

Fig. 1 Cd and Pb concentrations in roots and shoots of cole under single and joint toxicity. The same letters for the same tissue (roots or shoots) are not significantly different at 0.05 level ($P>0.05$). Mean±SD, $n=3$.

heavy metals increased in both the roots and the shoots of cole with each increment of Cd–Pb treatment level, but different characteristics displayed. For Cd, its concentration in the tissues of cole in the control (TS0) was significantly higher ($P<0.05$) than that in TS3 (Cd: 1.05 mg/kg) treatment. While for Pb, its concentration in roots and shoots in the control (TS0) were significantly ($P<0.05$) higher than that in TS2 (Pb: 150 mg/kg) and TS4 (Pb: 300 mg/kg) treatments, respectively. These results indicated that the joint toxic effects of Cd and Pb on cole could be weaker than their separate effects. In addition, the concentrations of Cd and Pb in different tissues under combined pollution occurred in a similar shoots>roots pattern for Cd, and roots<shoots pattern for Pb.

A further study of the Cd–Pb interaction on metal uptake in the cole is shown in Fig. 2, which displays variations of uptake under single and joint applications of Cd and Pb. To show the Cd and Pb accumulations in the same coordinates, the value of Cd uptake was magnified 10 times in the figure because Pb uptake was much larger than that of Cd. As can be seen in Fig. 2, the comparative features of metal uptake under different pollution levels was $\mathrm{Cd_S}>\mathrm{Cd_J}$ (hereinafter the subscript S or J represents single or joint application of Pb and Cd, respectively) under all treatments except for TS8, and $\mathrm{Pb_S}>\mathrm{Pb_J}$ under all treatments. These results elucidate the interaction of these two heavy metals under joint application. Adding Pb would reduce the accumulation of Cd in all tissues of cole, and therefore, the accumulation of Cd under joint application was lower than that under single application. Furthermore, adding Cd also had the same effect on Pb accumulation in the roots and shoots of cole, leading to $\mathrm{Pb_S}>\mathrm{Pb_J}$. Consequently, the interaction of Cd and Pb was antagonistic when tested cole absorbed Cd and Pb under circumstances of joint application. However, when the concentration of Pb

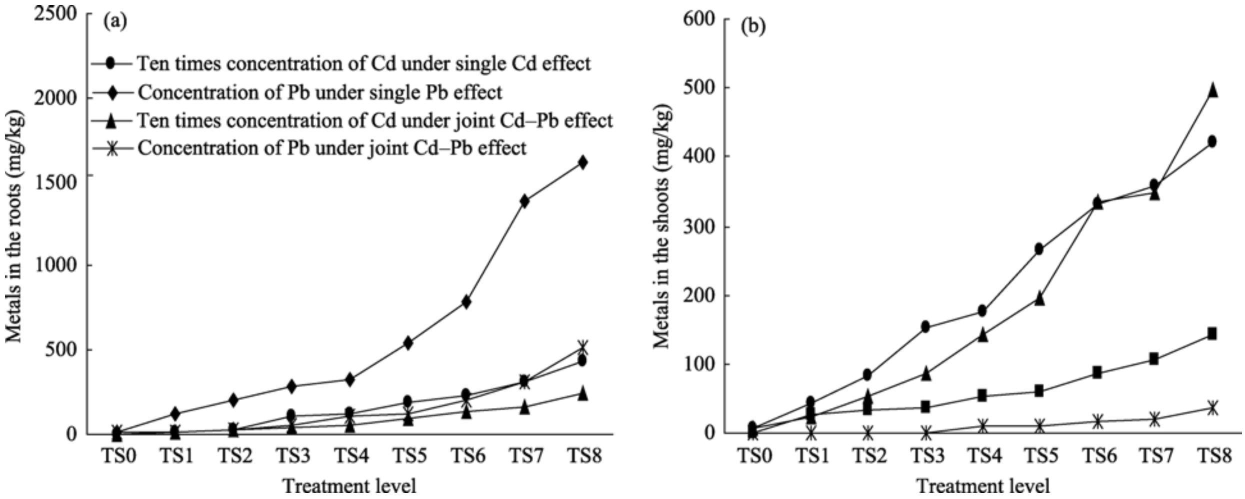

Fig. 2 Interaction of Cd and Pb to the uptake of heavy metals in roots and shoots of cole

was considerable, such as 1,500 mg/kg, the synergistic effect of Pb changed. The higher Pb concentration induced the higher uptake of Cd in the shoots of cole. This result was perhaps caused by the different adsorptive characteristics of Pb and Cd. The adsorption of the coexisted heavy metals decreased with an increase in the concentration of the added metal (Adel, 2008). In the case of higher Pb stress, more risks to plants would occur when adsorption amounts of Cd were saturated in the soil.

2.3 Impact of Cd and Pb interaction on heavy metal concentration and translocation in cole

The bio-concentration factor (BCF, the ratio of metal concentration in plant tissues at harvest to the initial concentration of metals in the external environment) and translocation factor (TF, the ratio of metal concentration in a plant's aerial parts and roots) could indicate the transfer capacity of heavy metals in soil-plant systems (Zayed et al., 1998; Marchiol et al., 2004; Shao et al., 2005). The higher values of BCF and TF indicate that increased amounts of heavy metals are concentrated and translocated from the soil to the roots and shoots of plants (Sutapa et al., 2007). Baker (1981) has distinguished three types of plants: accumulator, excluders, and indicator plants. In accumulator plants, the BCF is >1, in excluder plant the BCF and TF are <1, while in indicator plants, the BCF is near 1. BCF and TF are important parameters in the studies of heavy metal uptake. Therefore, these indicators can be used to explain the transfer capacity of Cd and Pb under the three scenarios examined by this experiment, and then to draw conclusions about the interaction of Cd and Pb through the comparative studies.

2.3.1 Impact of Cd application on Cd transfer capacity in different tissues of cole

The BCF and TF calculated for cole under Cd application are shown in Fig. 3a. The reported BCF and TF values are between 1.0 and 11.0, and 1.0 and 5.9, respectively. All values were greater than 1, which indicated that cole had a strong ability to uptake Cd from soils and translocate Cd from roots to shoots. These findings indicate that the tested cole has a strong attraction to Cd. Once Cd has entered the soil planted with cole through the medium of sewage irrigation or fertilization, it is easily transferred to the aboveground tissues of cole. Figure 3a shows the results comparing BCF and TF under the same treatment levels. At all treatment levels but the control (TS0), BCF was greater than TF. The BCF was 1.5 to 10.6 times larger than the TF under the same treatment level. The results indicate that the transfer capacity of Cd at the soil-root interface is stronger than that at the root-shoot interface. Therefore, the main location hindering Cd transfer was the root-shoot interface of the cole.

2.3.2 Impact of Pb application on Pb transfer capacity in different tissues of cole

As shown in Fig. 3b, BCF varied between 0.5 and 1.2,

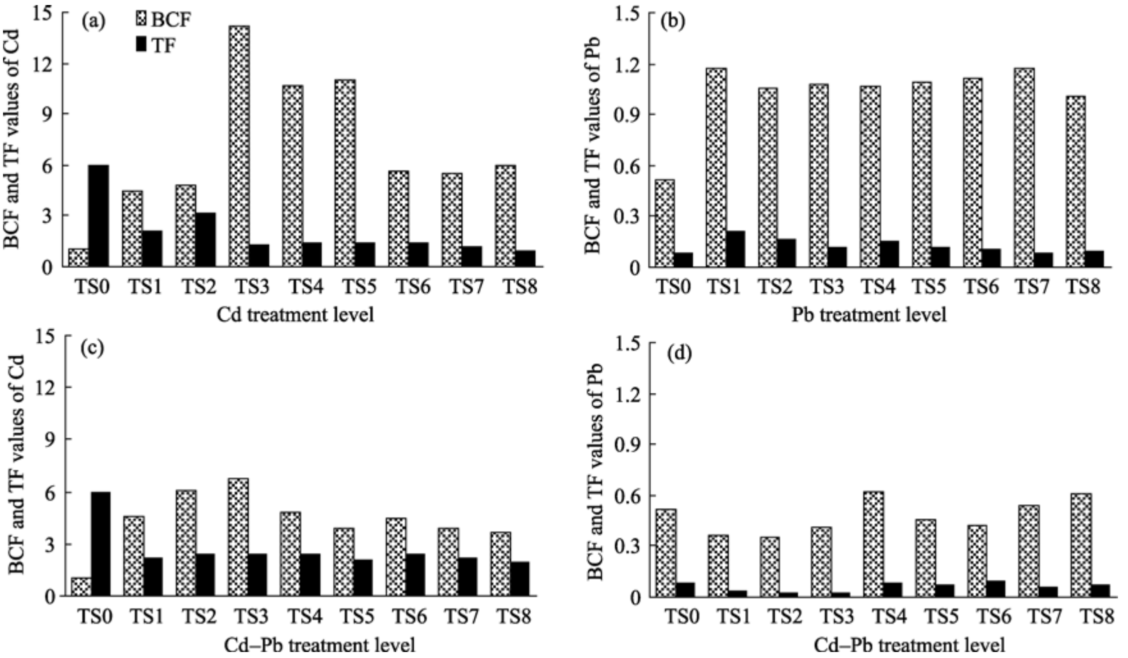

Fig. 3 The bio-concentration factor (BCF) and translocation factor (TF) of heavy metals at different Cd, Pb, Cd–Pb treatments in the soil-cole system

and TF varied from 0.08 to 0.2. Among the BCF values, all were greater than 1 (1.0–1.2) except for the control (TS0), which indicated that there was a relatively strong ability to concentrate Pb in the soil-root interface under the condition of Pb stress. Furthermore, because BCF was greater than TF (the bio-concentration factor was 5.5 to 11.4 times larger than the translocation factor), more Pb was concentrated in the roots of cole, and therefore, the main location hindering Pb transfer was the root-shoot interface of the cole.

2.3.3 Impact of Cd and Pb interaction on Cd and Pb transfer capacity in different tissues of cole

Under the condition of Cd–Pb treatment, the BCF and TF values of Cd were from 1.0 to 6.7 and 2.0 to 5.9, respectively (Fig. 3c). Similarly to Cd stress, there was a strong concentration and translocation ability of the tested cole. Compared with TF, BCF was still relatively high under all treatment levels except for the control (TS0). The BCF factor was 1.8–2.8 times larger than the TF. The results implied that the main location hindering Cd transfer was the root-shoot interface of the cole. BCF and TF values of Pb varied from 0.3 to 0.6 and 0.02 to 0.08, respectively (Fig. 3d), which indicates that the roots and shoots of the tested cole acted against Pb uptake. Moreover, the BCF was 4.7 to 21 times larger than the TF, i.e. Pb had a low translocation capability at the root-shoot interface.

Comparative studies which focused on the impact of Cd and Pb interaction on the concentration and translocation actions of Cd and Pb in the tested cole were carried out (Fig. 4). The BCF and TF of Cd and Pb under single and joint effects are shown in the same coordinate. The variation characteristics of BCF and TF in most treatment levels under the two effects were: $Cd_{BCF,S}>Cd_{BCF,J}$, $Cd_{TF,S}>Cd_{TF,J}$, $Pb_{BCF,S}>Pb_{BCF,J}$, $Pb_{TF,S}>Pb_{TF,J}$. Although $Cd_{BCF,J}>Cd_{BCF,S}$ and $Cd_{TF,J}>Cd_{TF,S}$ under TS1 and TS2 treatments, the results could not be used to estimate the interaction of Cd and Pb, because the difference was not significant ($P>0.05$). As a result, the characteristics indicated that the interaction of Cd and Pb was antagonistic in the tested cole. The addition of Cd would reduce the accumulation and translocation ability of Pb in roots and shoots of the tested cole, and the addition of Pb also did the same action for the tested cole to transfer Cd.

3 Discussion

Heavy metals with certain concentrations can reduce or increase the biomasses of plants. Reduced biomass

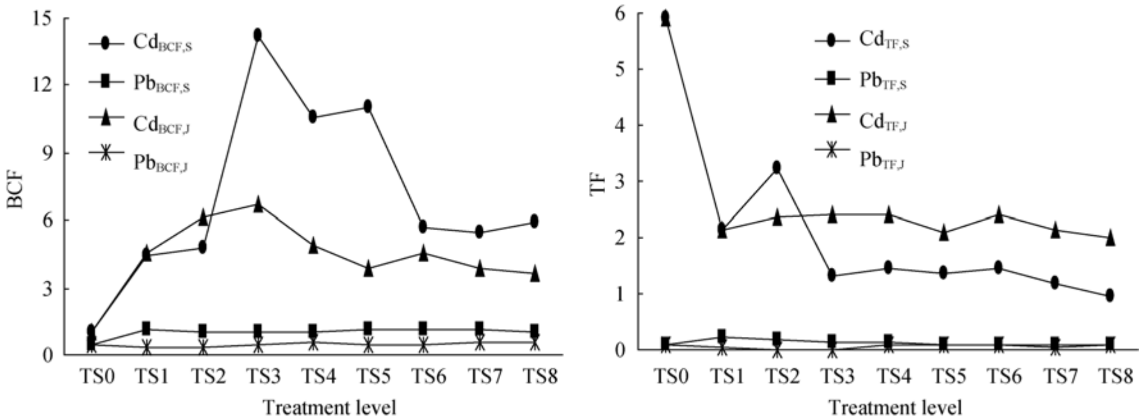

Fig. 4 Interaction of Cd and Pb to bio-concentration factor (BCF) and translocation factor (TF) of cole

has been reported for halophytes (Salma et al., 2012) and hyperaccumulator plants (Yang et al., 2005). Increased biomass has been reported in three ornamental plants with acceptable Cd concentration levels (Liu et al., 2008). The increase in biomass may involve inhibition of cell division as well as cell elongation (Yuan et al., 2011). In this study, most of the decreases or increases in plant wet weight caused by the toxicity of Cd, Pb and Cd–Pb were insignificant. The results also indicated that the tested cole had a higher tolerance to Cd or Pb contaminated soil. It was difficult to judge contamination degree from the cole's exterior response.

Cd is one of the elements that can easily be absorbed by plants and transported to shoots, even in trace concentrations (Jarvis et al., 1976). Furthermore, Cd concentration in plant tissues often increases with each incremental increase of Cd in the soil. It was difficult to reach a consensus on the distribution tendencies once Cd enters into the plant roots. Some research showed that the distribution of Cd concentrations in different plant tissues varies from plant to plant. For instance, the order of Cd concentrations in tomato, green pepper, and peppermint plants was roots> shoots>leaves, while it was found to be roots>leaves> shoots for green bean (Chi and Xu, 1995; Zheljazkov and Nielsen, 1996; Li et al., 2007), and shoots>roots in cole and Chinese cabbage (Lu et al., 2005; Fang et al., 2006). The difference in the distribution of Cd could be attributed to the rhizosphere biology (Travis et al., 2003). Root exudates, which secreted by different plant species, may change the chemical and physical properties of the soil, and then affect the ability to accumulate Cd (Xue et al., 2005; Petr et al., 2011).

Pb is an element which is difficult to be absorbed by plants because Pb can react with the components of the soil to form complexes or chelate and so form insoluble compounds, such as $PbCO_3$, $PbSO_4$, and $Pb(OH)_2$ (Zheng, 2008). Many authors reported that lead is low in mobility, and usually accumulates in roots rather than shoots of plants or crops (Liu et al., 2002; Lu et al., 2005). Zhou et al. (2008) reported that 79%–88% of Pb in *Potentilla griffithii* var. *velutina* accumulated in the roots and was mainly distributed in the cell walls and soluble parts of the ribosomes. Marmiroli et al. (2005) identified that Pb would form a complex with oxygen at the cell walls in the roots of the European walnut. Pb, which is a "soft" cation, shows a strong affinity for the organic ligands and tends to form inner-sphere complexes (Zaccone et al., 2007). This is also an important reason why it is difficult for Pb to transfer from roots to shoots. However, some results showed that Pb concentrations were lower in the roots than in the shoots of hot pepper and celery (Li et al., 2004; Cui and Xia, 2006; Li et al., 2007). The difference might be caused by the change of transferred direction of Pb. For example, when the direction is down-to-up (as in the condition of the pot experiment), Pb is prone to accumulate in the roots of plants. When the direction is up-to-down (under field conditions), Pb is prone to accumulate in the shoots.

This study demonstrated that the interaction between Cd and Pb in soils influenced the accumulations of heavy metals in the cole. It is worthwhile to note that the concentration of Pb in soil affected Cd accumulation in the cole. A similar finding was reported by Xin et al. (2010), that the presence of Pb enhanced the Cd accumulation in the cole. Besides the concentration of heavy metals, plant variety was also an important influence on Cd and Pb interactions. For instance, the joint application of Cd and Pb was antagonistic in soybean while it was synergistic or additive in tobacco (Guo and Zhou, 2003; Wang et al., 2007). The different ecological effects of Cd and Pb interaction were caused by the different behaviors of competitive adsorption, complexation-chelation, and enzyme activity (Yang and Liu, 2000; Guo and Zhou, 2003). The adsorption of heavy metals is very important in determining the capacity of soils to respond to the introduction of these pollutants into soil systems. Pb would occupy the sorption position of Cd in soils with the increment of maximal Pb adsorption capacity, and therefore enhance the availability of Cd. This mechanism might lead to synergism between Cd and Pb (Song and Guo, 1996; Lu et al., 2005; Wang et al., 2007). Antagonism might be generated by the formation of some compounds with organic matter. Cd and Pb have a similar chemical affinity with organic matter in plants due to the same chemical valence. When they enter plants simultaneously, they compete with each other and facilitate precipitation reaction (An, 2004). In addition, the adsorptive characteristics of Cd might be affected by the biphasic behavior (that is, an initial fast reaction and then a slower reaction) of Pb's adsorption kinetics, especially in higher concentration (Heike, 2004).

The variations of BCF and TF of the two heavy metals of Cd and Pb were related to their interaction in the soil-cole system. Addition of Cd and Pb restrained the transfer capacity of heavy metals which co-exist in the system. Zhu and Wang (2004) reported that the joint application of Cd and Pb would facilitate the occurrence of precipitation processes in plant roots, i.e. the two metals showed an evident antagonism at the transfer of each other. However, Zheng et al. (2002) found that joint Cd and Pb application increased the BCF of the paddy, which absorbed more heavy metals and strengthened the transfer capacity of metals in crops. The reason might be that the soils and the roots of paddy are prone to absorb Pb rather than Cd, thus activating more elemental Cd to transfer (Zheng et al., 2002). In summary, due to the effects of multiple factors, such as the variation of heavy metal speciation, the transfer balance of heavy metals in plants, and the distribution equilibrium of heavy metals in the soil and plant system, the joint application of Cd and Pb causes different reactions in different plants, which also implies the underlying complexity of the soil-plant system.

4 Conclusion

The results of the present study revealed that the cole grown in different scenarios showed varied responses. Cole (*Brassica campestris* L) which were planted in arid oasis soils showed high tolerance to single and combined Cd and Pb contaminated soil. We found it hard to judge contamination degree from the cole's exterior response. It implies that cole is not a suitable vegetable to be planted in this region. The analysis results highlighted that, compared with the application of either Pb or Cd, the joint application of Cd and Pb played a remarkable role in metal uptake, concentration, and translocation by the tissues of the tested cole. The interactive effect of Cd and Pb could weaken the cole's capability of uptake, concentration, and translocation of heavy metals. In other words, the interaction of these two heavy metals is antagonistic in the arid oasis soils-cole system. Moreover, it was noteworthy that when the concentration of Pb was very high, the antagonistic effect of Pb would change to an assistive one. Therefore, we should pay special attention to Cd and Pb combined pollution in arid soils where cole is grown.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (51178209, 91025015) and the Fundamental Research Funds for the Central Universities in Lanzhou University (lzujbky-2011-66). The authors would like to place on record their sincere thanks to Linze Inland River Basin Re-

search Station, Chinese Ecosystem Research Network.

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