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Restoration of Cadmium (Cd) Pollution Soils by Use of Weeds

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1. Introduction

Soil contamination by heavy metals such as cadmium (Cd), copper and mercury has become a big concern particularly in metal plating plants, mining sites and surrounding areas as well as residential area and farmlands in the river downstream region neighboring these facilities. In some cases, heavy metals in soils leach into river water and then diffuse onto farmlands with irrigation, resulting in relatively low levels of heavy metals being spread into wider areas rather than being localized in high concentrations (Asami 1972). Therefore, when civil engineering methods including addition of topsoil and removal of contaminated soils are used for remediation of heavy metal contaminated soils, a large amount of uncontaminated fresh soil and large disposal areas are required, which creates a bottle neck for the remediation. Thus, the development of a new remediation technology to replace the conventional civil engineering technology is needed. The remediation technology for soils contaminated with harmful substances using plants is called phyto-remediation, and its potential has demonstrated by many researchers (Elizabeth 2005). However, this new remediation technology is in the initial stage even at present, except for some cases, e. g., the remediation of oil-spilled soil using Italian ryegrass (Kaimi *et al.* 2006) and that of Cd-contaminated paddy soil using rice plants (Honma *et al.* 2009) are currently being conducted, because no appropriate remediation plant and no remediation systems have been found and developed. Thus, weed species, possessing high adaptability to environment, have been pointed out as a suitable plant for soil remediation. Although research on phyto-remediation using weeds has just begun and there are many issues which need to be resolved, this remediation technique is expected to become a valuable technology for the alleviation of heavy metal contaminated soils in the near future.

This chapter focuses on the potential of weed for remediation of Cd-contaminated soils. In order to better understand phyto-remediation by weeds, the rationale of using weeds for Cd remediation and the biological characteristics of weeds are explained. Herbaceous plants are classified into several groups such as crops, grasses, weeds and wild plants. Crops are plants that require artificial protection such as pest control, fertilization, watering and etc., ; on the other hand, weeds can thrive under severe growth conditions. For example, asiatic plantain (*Plantago asiatica*) in highly compacted soil areas, crabgrass (*Digitaria cillari*) in dry regions, annual bluegrass (*Poa annua*) in cool wet regions, field horsetail (*Equisetum arvense*) in acidic soils, saltbush (*Atriplex subcordata*) in salt-accumulation areas, and broomsedge

(*Andropogon virginicu*) in phosphate-deficient soils can grow vigorously under these conditions (Takematsu and Ichizen 1987, 1993, 1997). For plants, not only Cd contaminated soil but also various environmental factors such as low temperature, aridity, low sunlight (shade), nutrient deficiency (infertile soil), poorly drained soil, competitions between plants for water, nutrition, and light, and allelochemicals generated from plants are regarded as adverse growth conditions. Therefore, remediation plant (plant using for restoration of Cd pollution soils) must be able to grow under these adverse weather and soil conditions. On the other hand, several methods are considered in phyto-remediation, and the capability of remediation plants are depending on the approach considered. Unlike organic compounds, Cd cannot be degraded; therefore, absorption (phyto-extraction) and fixation (phyto-stabilization) are the most effective methods proposed for Cd-remediation. Phyto-extraction is the chemical removal method of Cd by absorption through the roots and accumulation in shoots, followed by plant harvesting. Phyto-stabilization is a method of retaining Cd on the adjacent surface of plant roots. Mulching, which prevents the run-off of Cd contaminated soil into the surrounding non-polluted area by the root system extending in soils, can also be considered for phyto-remediation technologies. Particularly in slopes, mulching with plants may be prior to Cd extraction from the contaminated soils.

Among several screening studies on the remediation plants conducted, it is demonstrated that *Athyrium yokoscense* is highly tolerant to heavy metals (Nishizono *et al.* 1987); however, its biomass is extremely small to be valuable as a remediation plant. The plant species best suited for phyto-extraction require the ability to accumulate large amounts of Cd in their shoots, extension of their roots into soil, rapid growth and a long growing period. The plant species suitable for mulching require the ability to extend their roots into soil, a high LAI (leaf area index) value; plants with a high LAI value can reduce the physical strength of rainfall to scour soil, large biomass, rapid growth and long growing period. Furthermore, it is important that whether seeds and vegetative reproductive organs such as rhizomes and tubers can be inexpensively supplied in large quantities for the remediation plant. As compared with crops, weeds are generally superior in several points such as environment adaptability and Cd tolerance and accumulation, however, are inferior in seed supply (Table-1). Thus, in case when seeds of remediation plants (weeds) are difficult to obtain, top soil (seed bank) of non-pollution areas where weeds are densely grown, are available. As well as Cd tolerant weed species, Cd sensitive weed species are also useful for Cd remediation (Table-2); e. g., results of phyto-remediation at the pollution area can be evaluated by distribution and biomass of the Cd sensitive weed species such as *Arenaria serpyllifolia*, *Geranium carolinianum* and *Phseolus aureas*.

Factors	weeds	Crops
Cd tolerance	Superior	Inferior
Cd accumulation	Superior	Inferior
Adaptability to environment *	Superior	Inferior
Pest tolerance (disease, insect)	Superior	Inferior
Seed or seedling supply	Inferior	Superior
Growth speed	Superior	Inferior

*: drought, cool, shade, wet, salinity and infertile land tolerance

Table 1. Comparison of weeds and crops as a Cd remediation plants

Family name	Scientific name	I ₅₀ value (mg Cd kg ⁻¹)*
Onagraceae	<i>Epilobium angustifolium</i>	1.5
Geraniaceae	<i>Geranium carolinianum</i>	1.3
Leguminosae	<i>Phaseolus angularis</i> (cv. Tanba Dinagon)	2.0
	<i>Phaseolus aureus</i>	0.8
	<i>Trifolium fragiferum</i>	1.7
Cruciferae	<i>Rorippa cantoniensis</i>	2.3
Caryophyllaceae	<i>Arenaria serpyllifolia</i>	1.1
	<i>Stellaria alsine</i> var. <i>undulata</i>	1.6
	<i>Stellaria graminea</i>	1.9
Polygonaceae	<i>Antenoron filiforme</i>	1.4
Compositae	<i>Eclipta prostrata</i>	1.5
	<i>Sonchus asper</i>	1.8

* Susceptible weed species having ≤ 2 of I₅₀ value (mg Cd kg⁻¹): the concentrations of Cd causing a 50% reduction in fresh weight of shoot to that of the untreated plant grown under sand culture conditions

Table 2. Susceptible weed species to Cd

2. Sensitivities of weeds to Cd

About 6,000 plant species are accounted as a weed in the world. Cd sensitivities weeds vary depending on species (Fig. 1 and Fig. 2). In this section, Cd sensitivity and Cd content of weeds are referred.

It is reported that *Arabidopsis halleri* and *Thlaspi caerulescens* are highly tolerant to Cd (Bert et al. 2003; Brown et al. 1995); however, *Hibiscus cannabinus*, *Portulaca oleracea*, *Xanthium strumarium*, *Amsinckia barbata*, *Anthoxathium odoratum*, *Arthoraxon hipidus*, *Digitaria ciliaris*, *Echinochloa crus-galli* var. *praticola*, *Lolium multiflorum*, *Panicum bisulcatum*, *Paspalum dilatatum*, *Poa pratensis* and *Setaria faberi* are have also been reported to have a high tolerance to Cd (I₅₀: > 30 mg Cd Kg⁻¹) (Abe et al. 2006) (Table-3). When the weed habitat is considered, *E. crus-galli* var. *praticola*, *D. ciliaris*, *S. faberi* and *P. dilatatum*, *A. odoratum*, *L. multiflorum* and *P. pratensis* are the most suitable for saturated, semi-arid, warm and cold conditions, correspondingly. When the weed biomass is considered, *X. strumarium* growing up 1–2 m is the most suitable for Cd extraction. When the life-span of weed is considered, *A. odoratum*, *P. bisulcatum*, *P. dilatatum*, *P. thunbergii*, and *P. pratensis* are perennials, and particularly *P. pratensis* is a long-lived grass that can survive more than a few decades; therefore, phyto-remediation will be proceeded continuously once perennial weed species such as *P. pratensis* is introduced into the Cd pollution area.

On the other hand, there are great variations on Cd tolerance among weed species. However, the tolerance can be predicted when they belong to the same family. Abe et al. (2006) reported that *Gramineae* and *Compositae* weed species were tolerant, while *Leguminosae* and *Cruciferae* weed species were sensitive according to the pot tests conducted



Fig. 1. Susceptibility of *Echinochloa crus-galli* var. *crus-galli* to Cd

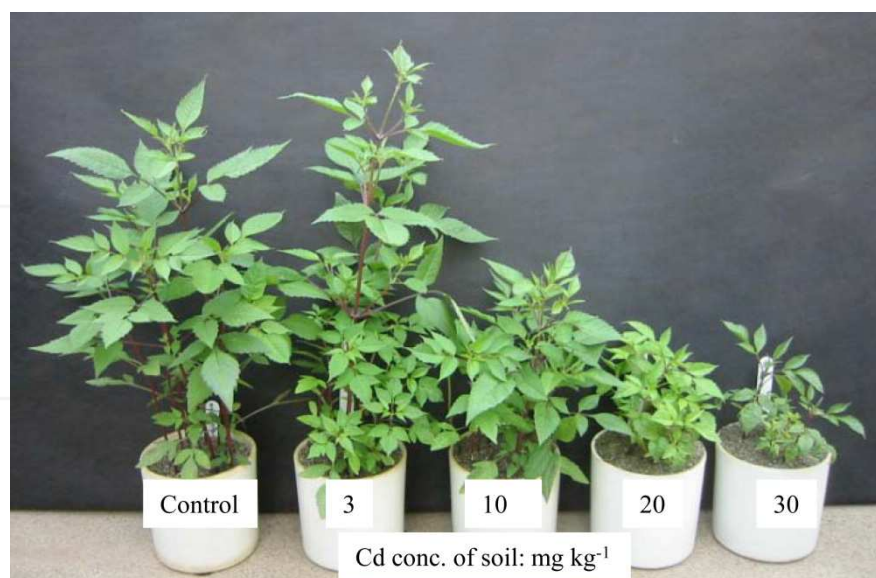


Fig. 2. Susceptibility of *Bidens frondosa* to Cd

Family name	Scientific name
Malvaceae	<i>Hibiscus cannabinus</i>
	<i>Malva sylvestris</i>
Caryophyllaceae	<i>Silene ameria</i>
Portulacaceae	<i>Portulaca oleracea</i>
Phytolaccaceae	<i>Phytolacca americana</i>
Compositae	<i>Xanthium atrumarium</i>
Boraginaceae	<i>Amsinckia barbata</i>
Gramineae	<i>Anthoxanthum odoratum</i>
	<i>Anthraxon hispidus</i>
	<i>Digitaria ciliaris</i>
	<i>Echinochloa crus-galli</i> var. <i>pracilola</i>
	<i>Lolium multiflorum</i>
	<i>Panicum bisulcatum</i>
	<i>Paspalum dilatatum</i>
	<i>Poa pratensis</i>
	<i>Setaria faberi</i>
	<i>Agrostis stolonifera</i>

Tolerant weed species having ≥ 30 of I_{50} value (mg Cd kg^{-1}): the concentrations of Cd causing a 50% reduction in fresh weight of shoot to that of the untreated plant grown under sand culture conditions

Table 3. Tolerant weed species to Cd*

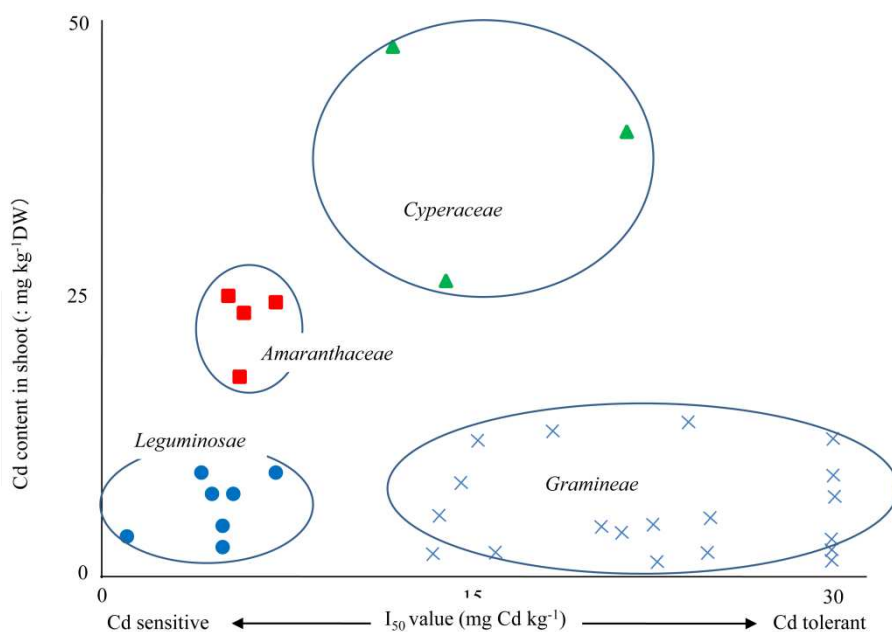


Fig. 3. Relation of susceptibility (I_{50} value) to Cd and Cd content in shoot of weeds belonged to 4 families

on about 200 weed species (Fig. 3 and Table-4). This result indicated that the Cd concentrations of soils in a certain areas could be predicted by analysis of weed vegetation. Among weed species belonging to *Gramineae* and *Leguminosae* species, appropriate Cd remediation plant and Cd indicator may be found.

Family name	Total number of plant species tested	Number of plant species (%)				Mean of I_{50} values (Cd mg kg ⁻¹)
		Group 1	Group 2	Group 3	Group 4	
<i>Caryophyllaceae</i>	17 (100%)	13 (76.4%)	2 (11.8%)	1 (5.9%)	1 (5.9%)	8.8
<i>Cruciferae</i>	15 (100%)	10 (66.7%)	5 (33.3%)	-	-	7.5
<i>Leguminosae</i>	15 (100%)	15 (100%)	-	-	-	4.6
<i>Compositae</i>	31 (100%)	13 (41.9%)	12 (38.7%)	4 (12.9%)	2 (6.5%)	13.2
<i>Gramineae</i>	45 (100%)	-	15 (33.3%)	18 (40.0%)	12 (26.7%)	22.6

Group 1, I_{50} value <10; Group 2, I_{50} value 10 ~ <20; Group 3, I_{50} value 20 ~ <30; Group 4, I_{50} value \geq 30

Table 4. Susceptibilities of *Caryophyllaceae*, *Cruciferae*, *Leguminosae*, *Compositae* and *Gramineae* weed species to Cd

3. Cd accumulation abilities of weeds

High Cd accumulation ability as well as Cd tolerance is required for the remediation plants; however, there is no positive correlation between Cd accumulation and Cd sensitivity. Weed species with highly tolerant to Cd can be divided into two groups: weeds that absorb hardly Cd (Cd exclusion type) and weeds that absorb and detoxify Cd (Cd detox-accumulation type). Abe *et al.* (2008a) revealed from a pot test that *Cichorium intybus* (77 mg kg⁻¹ DW) and *Matricaria chamomilla* (64.4 mg kg⁻¹ DW) can accumulate large amounts of Cd in their shoots; these accumulations are more than *Polygonum thunbergii* (56.2mg kg⁻¹ DW) that is known as a hyper-Cd accumulator (Shinmachi *et al.* 2003) (Table-5). The mechanism involved in Cd accumulation by weeds are still not well understood; however, it can be predicted that the absorbed Cd is detoxified by forming chelates with phytochelatin, malic acid, and citric acid in plants. On the other hand, *Gramineae* plant, e. g., *Oryza sativa* (cv. Milyang) accumulate high concentrations of Cd (>100 mg kg⁻¹ DW) in its roots but accumulate little Cd in their shoots, in contrary, *Compositae* plant, e. g., *Bidens frondosa* accumulate low concentration of Cd in the root but accumulate much Cd in its shoots (Table-6, Table-7, Table-8). The Cd content ratio between roots and shoots (SR ratio) of *C. intybus* (3.56; it means that shoots contain 3.56 times more Cd than roots) is higher than that of *O. sativa* (cv. Milyang; 0.02); therefore, the results indicate that the Cd is easily translocated from roots to shoots in dicotyledons as compared to monocotyledons (*Gramineae*) (Table 6). Therefore, *Bidens frondosa*, *B. pilosa* and *Amaranthus viridis*, which accumulate more Cd in their shoots than in roots and possess a large biomass, may be useful for phyto-extraction.

Family name	Scientific name	Cd conc. (mg kg ⁻¹ dry weight)
Plant species with relatively high Cd conc.		
Compositae	<i>Cichorium intybus</i>	77.0
Compositae	<i>Matricaria chamomilla</i>	64.4
Polygonaceae	<i>Polygonum thunbergii</i>	56.2
Cyperaceae	<i>Cyperus brevifolius</i> var. <i>leiolepis</i>	48.3
Cruciferae	<i>Sisymbrium orientale</i>	48.2
Cruciferae	<i>Sisymbrium altissimum</i>	48.2
Compositae	<i>Picris echinoides</i>	41.0
Plant species with relatively low Cd conc.		
Gramineae	<i>Oryza sativa</i> (cv. Milyang 42)	0.8
Gramineae	<i>Panicum dichotomiflorum</i>	1.0
Gramineae	<i>Dactylis glomerata</i>	1.2
Plantagineaceae	<i>Plantago virginica</i>	1.4
Gramineae	<i>Panicum bisulcatum</i>	1.5
Onagraceae	<i>Oenothera biennis</i>	1.8
Gramineae	<i>Digitaria ciliaris</i>	1.9
Leguminosae	<i>Sesbannia exaltata</i>	2.1
Gramineae	<i>Echinochloa crus-galli</i> var. <i>prachicola</i>	2.1

Table 5. Weed species which accumulate relatively high (≥ 30) and low (≤ 3) concentrations (mg kg⁻¹ DW) of Cd in their shoots

Family name	Scientific name	Cd conc. (mg kg ⁻¹ dry weight)
Plant species with relatively high Cd conc.		
Onagraceae	<i>Oenothera biennis</i>	171.9
Convolvulaceae	<i>Calystegia sepium</i> var. <i>1 americana</i>	122.6
Leguminosae	<i>Cassia obtusifolia</i>	122.2
Gramineae	<i>Oryza sativa</i> (cv. Milyang 25)	117.5
Labiatae	<i>Salvia plebeia</i>	116.6
Gramineae	<i>Festuca arundinaceae</i>	115.4
Caryophyllaceae	<i>Silene dioica</i>	113.0
Malvaceae	<i>Sida rhombifolia</i>	111.9
Plant species with relatively low Cd conc.		
Compositae	<i>Bidens pilosa</i>	7.7
Compositae	<i>Bidens frondosa</i>	9.4
Compositae	<i>Lactuca indica</i>	11.4
Polygonaceae	<i>Rumex crispus</i> subsp. <i>japonicus</i>	12.2
Compositae	<i>Sochus oleraceus</i>	14.2
Cruciferae	<i>Camelina sativa</i>	15.9

Table 6. Weed species which accumulate relatively high (≥ 110) and low (≤ 16) concentrations (mg kg⁻¹ DW) of Cd in their roots

Family name	Scientific name	Shoot Cd content ($\mu\text{g plant}^{-1}$)
Cyperaceae	<i>Cyperus brevifolius</i> var. <i>leiolepis</i>	50.0
Polygonaceae	<i>Polygonum thunbergii</i>	49.7
Compositae	<i>Bidens frondosa</i>	40.5
Compositae	<i>Cichorium intybus</i>	38.8
Cyperaceae	<i>Cyperus globosus</i>	30.3
Compositae	<i>Bidens pilosa</i>	24.1
Amaranthaceae	<i>Amaranthus viridis</i>	22.5
Malvaceae	<i>Hibiscus cannabinus</i>	21.4
Cruciferae	<i>Sinapis alba</i>	21.4
Cruciferae	<i>Sisymbrium altissimum</i>	21.4
Caryophyllaceae	<i>Silene notiflora</i>	21.1
Amaranthaceae	<i>Amaranthus hybridus</i>	20.7

Table 7. Weed species which accumulate relatively high ($\geq 20 \mu\text{g plant}^{-1}$) content of Cd in shoots

Family name	Scientific name	Cd conc. (mg kg^{-1} dry weight)
Plant species with relatively high shoot-root ratio		
Compositae	<i>Cichorium intybus</i>	3.56
Compositae	<i>Bidens frondosa</i>	3.30
Compositae	<i>Lactuca indica</i>	2.27
Compositae	<i>Bidens pilosa</i>	2.21
Plant species with relatively low shoot-root ratio		
Onagraceae	<i>Oenothera biennis</i>	0.01
Plantaginaceae	<i>Plantago virginica</i>	0.02
Gramineae	<i>Oryza sativa</i> (cv. Milyyang 42)	0.02
Gramineae	<i>Dactylis glomerata</i>	0.03

* shoot-root ratio : the ratio of Cd conc. in shoot and root in plant

Table 8. Weed species which have relatively high (≥ 2.0) and low (≤ 0.03) shoot-root ratios*

4. Utilization of PGRs to Cd remediation by use of weeds

So far, various cultivation methods and materials have been used to control the Cd elution into soils (Turgut *et al.* 2004; Hattori *et al.* 2006); e. g., treatment of Calcium materials and deep flooding (rice paddy fields) have been used to diminish Cd elution into the free water in soils; on the other hand, drying of soil and treatment of chlorides and EDTA have been used to enhance the Cd elution. In addition to these materials, it is reported that certain plant hormones directly affect the growth of remediation plants. Abscissic acid suppresses a decrease in chlorophyll content caused by Cd in *Brassica napus*, while 28-homobrassinolide mitigates the growth inhibition caused by Cd in *Cicer arietinum*. According to a hydroponic test using white Japanese millet (*Echinochloa frumentacea*) conducted by Abe *et al.* (2011), it was shown that HMI (3-hydroxy-5-methylisoxazole) at $2.5 \times 10^3 \text{ mmol/l}$ significantly reduced the growth inhibition (dry weight; % of control) of roots and shoots caused by Cd at $4.4 \times 10 \text{ mmol/l}$ from 4.2% to 23.9% and from 48.5% to 82.6%, respectively, while increasing Cd content ($\mu\text{g plant}^{-1}$) from

0.32 ± 0.08 to 0.53 ± 0.04 in roots. This result indicates that Cd tolerance of remediation plants can be further enhanced by HMI. (Fig. 4, Fig. 5, Fig. 6) HMI, plant growth regulator (PGR) that shows similar action to those of plant hormones, has been used as rooting agent for paddy rice (Ogawa and Ota 1976) and thus it is thought that HMI can be also easily applied for Cd remediation with weeds, particular in the mulching.

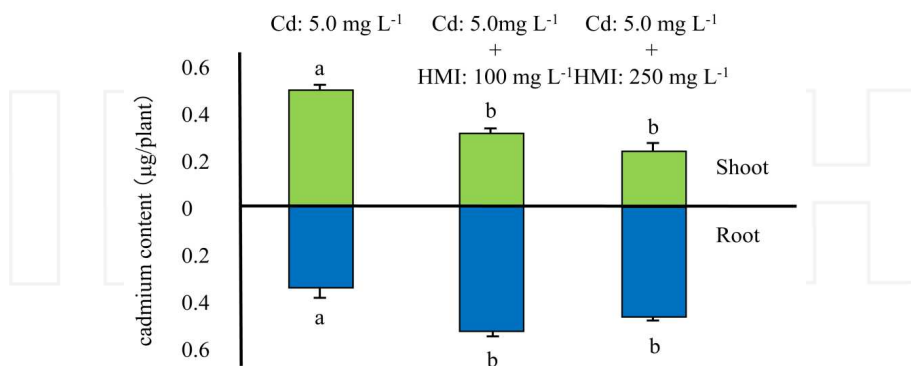


Fig. 4. Effect of HMI on Cd accumulation in shoot and root of *Echinochloa frumentacea*. The error bars represent the standard deviation of the mean (n=3). The means followed by the same letter within a column are not significantly different by Tukey's multiple range test ($p < 0.05$).

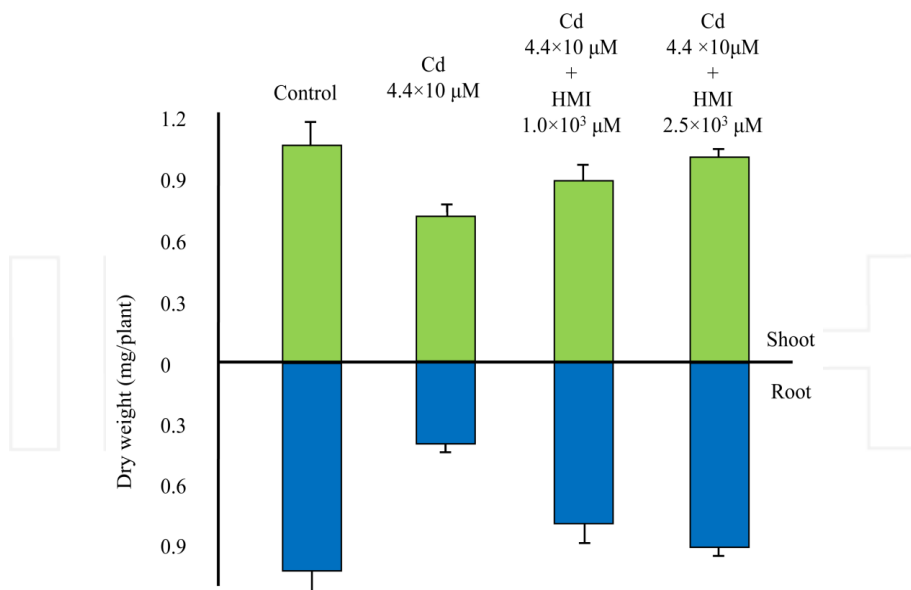


Fig. 5. Effect of HMI on *Echinochloa frumentacea* growth inhibited by Cd. The error bars represent the standard deviation of the mean (n=3).



Fig. 6. Mitigation effect of hymexazole (HMI; 3-hydroxy-5-methylisoxazole) against *Echinochloa frumentacea* growth injury caused by Cd

5. Goal and approach for the restoration of Cd pollution soils by use of Weeds

In general, Cd pollution of soils are distributed over wide ranges, and recovery of vegetation at the pollution area and Cd extraction from the soils require a long time; thus it is important to make a grand design on goals and approach of the remediation of Cd pollution soils using weeds based on long term foresight. The remediation approach

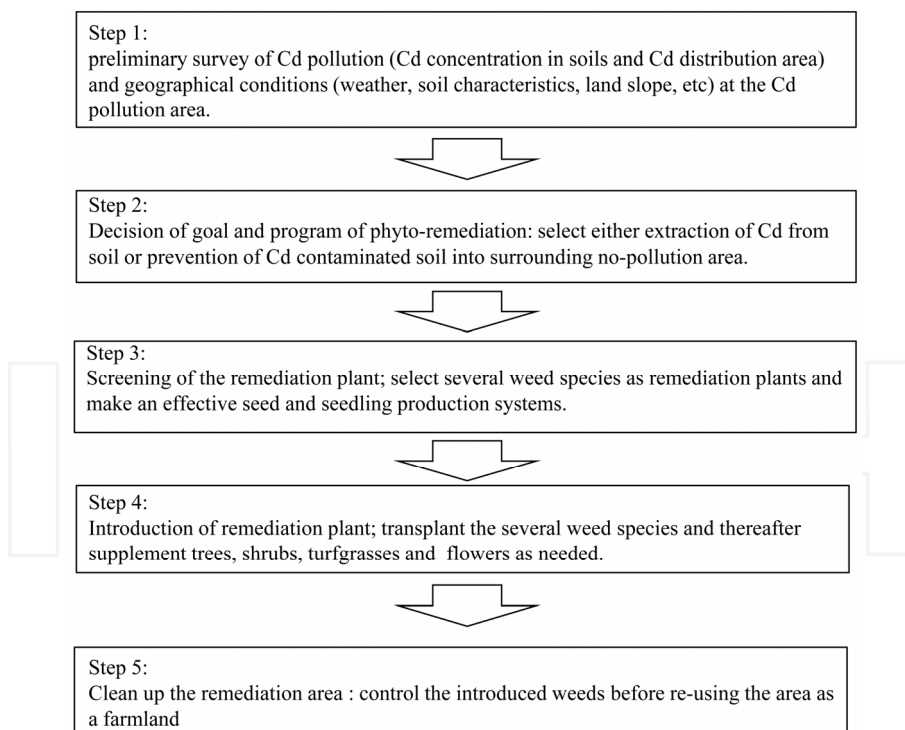


Fig. 7. Goal and approach of remediation of Cd pollution soils by use of weeds

depends on the not only Cd contamination levels in soil but also environmental and geographical conditions of the pollution areas, e. g., when the area is located in slopes, prevention of run-off of Cd contaminated soil by mulching should be preceded to Cd extraction. For the Cd remediation using weeds, several goals are suggested as follows; 1) prevention of Cd elution into the surrounding non-polluted areas; vegetation is restored by mulching with weeds and followed by introduction of grasses, turf grasses and shrubs as needed, but Cd extract is not involved in this case, 2) extraction of Cd from the pollution soils; Cd extraction is conducted by use of the remediation plants, and thereafter when post-mitigated area is reused as a farmland, introduced remediation plants (weeds) should be controlled completely by herbicides and practical methods before land reuses (Fig. 7). As mentioned above, Cd remediation approach varies with goals, however, preliminary survey of Cd concentrations in soil, weather conditions (temperature, sunlight and precipitation by month), physicochemical characteristics of soils, drainage, fertility and slope angle are needed regardless of the approach and the goal to decide the remediation plant (weed species) and the remediation methods (phyto-extraction, phyto-stabilization and/or mulching). Moreover, in some cases, repeated introduction of the remediation plants into the Cd pollution area may be required, because seed production of the plant is possibly be inhibited by Cd even when Cd tolerant plants are used. For example, it is reported that the number of seeds / plant of *Portulaca oleracea* var. *sativa*, which is tolerant to Cd, is inhibited by 65% at 20 mgkg⁻¹ of Cd (Abe *et al.* 2008b). Use of hormone and PGR may increase in the seed production and biomass of the remediation plants, and those seedlings habituated in the Cd contaminated soils before introducing them into the pollution areas, may be useful for the remediation.

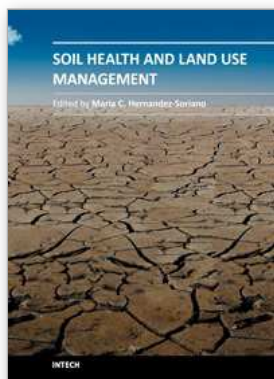
6. Conclusion

Weeds are highly adaptive to adverse environmental conditions compared to crops, which is a crucial factor to consider weeds for developing soil remediation technologies. However, it might be considerably more difficult to ensure the necessary seed and seedling supply of weeds compare to crops, which can hamper the development of potential remediation technique. Thus when weeds are used for restoration of Cd pollution soils, to develop an effective seed and seeding production systems may become a crucial requirement. Besides, the proposed phyto-remediation with weeds might be envisioned as a long term approach due to the time requirements of the approach. In general, there is a great tendency that Cd extraction is much spotlighted than other goals, however, supplying the soils abundant in organic matter which absorb Cd and keep it in the soils by transplanting of herbaceous plants including weeds; resulting in the prevention of the run-off of Cd contaminated soil into surrounding non-polluted areas, may be efficient in case that Cd pollution is distributed over the extensive area.

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Soils play multiple roles in the quality of life throughout the world, not only as the resource for food production, but also as the support for our structures, the environment, the medium for waste disposal, water, and the storage of nutrients. A healthy soil can sustain biological productivity, maintain environmental quality, and promote plant and animal health. Understanding the impact of land management practices on soil properties and processes can provide useful indicators of economic and environmental sustainability. The sixteen chapters of this book orchestrate a multidisciplinary composition of current trends in soil health. Soil Health and Land Use Management provides a broad vision of the fundamental importance of soil health. In addition, the development of feasible management and remediation strategies to preserve and ameliorate the fitness of soils are discussed in this book. Strategies to improve land management and relevant case studies are covered, as well as the importance of characterizing soil properties to develop management and remediation strategies. Moreover, the current management of several environmental scenarios of high concern is presented, while the final chapters propose new methodologies for soil pollution assessment.

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