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Effects of Double Harvesting on Heavy Metal Uptake by Six Forage Species and the Potential for Phytoextraction in Field

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ABSTRACT

The pollution of soils by heavy metals has dramatically increased in recent decades. Phytoextraction is a technology that extracts elements from polluted soils using hyperaccumulator plants. The selection of appropriate plant materials is an important factor for successful phytoextraction in field. A field study was conducted to compare the efficiency of six high-biomass forage species in their phytoextraction of heavy metals (Cd, Pb, and Zn) from contaminated soil under two harvesting strategies (double harvesting or single harvesting). Among the tested plants, amaranth accumulated the greatest amounts of Cd and Zn, whereas Rumex K-1 had the highest amount of Pb in the shoot under both double and single harvesting. Furthermore, double harvesting significantly increased the shoot biomass of amaranth, sweet sorghum and sudangrass and resulted in higher heavy metal contents in the shoot. Under double harvesting, the total amounts of extracted Cd, Pb and Zn (*i.e.*, in the first plus second crops) for amaranth were 945, 2 650 and 12 400 g ha^{-1}, respectively, the highest recorded among the six plant species. The present results indicate that amaranth has great potential for the phytoextraction of Cd from contaminated soils. In addition, the double harvesting method is likely to increase phytoextraction efficiency in practice.

Key Words: amaranth, harvesting strategy, high-biomass, hyperaccumulator plant, soil pollution

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INTRODUCTION

The pollution of soils by heavy metals has dramatically increased in recent decades due to the discharge of waste and wastewater from anthropogenic sources (Pacwa-Płociniczak *et al.*, 2011). Phytoextraction is a technology that extracts elements from polluted or mineralized soils by using hyperaccumulator plants, which accumulate pollutants/contaminants in harvestable organs and tissues that can then be removed from the field (Rascio and Navari-Izzo, 2011; Andreazza *et al.*, 2013). This technique offers the benefits of being *in situ*, low cost, and environmentally sustainable (Sharma *et al.*, 2007). However, field trials or commercial operations have successfully demonstrated that the phytoremediation of metals are limited (Maxted *et al.*, 2007). Only *Alyssum* species, which are hyperaccumulators of Ni, have been developed into a commercial-scale phytoremediation technology (Chaney *et al.*, 2007). The main limiting factor in the application of this technology is the low remediation efficiency of hyperaccumulators due to limited element accumulation in the shoot and restricted biomass production (Sarma, 2011).

The selection of appropriate plant materials is an important factor for successful phytoextraction in the field. Forage species may be good candidates under field conditions because of their potentially higher biomass, adaptability to specific environmental conditions, abundant seed production, deep-rooting habit, ease of cultivation and suitability for repeated cropping, which make them superior to many of the other currently known hyperaccumulators (Zhang *et al.*, 2010). Extensive research has been done on the heavy metal uptake of high-biomass forage species, such as alfalfa (*Medicago sativa*), vetiver (*Vetiveria zizanioides*) and tall fescue (*Festuca arundinacea*) (Chen *et al.*, 2004; Begonia *et al.*, 2005; Zaefarian *et al.*, 2013). Furthermore, their extraction capacity may be enhanced if suitable strategies, based on good agronomic practices and management, are adopted (McGrath *et al.*, 2006).

To enhance the efficiency of phytoextraction, chelates and organic acids, such as ethylenediaminetetra-

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acetic acid (EDTA), ethylenediaminedisuccinates (EDDs) and citric acid, have been added to contaminated soils to accelerate the uptake of heavy metals by plants (Leštan *et al.*, 2008; Almaroai *et al.*, 2012). However, the excessive addition of chelating agents in the field may result in secondary pollution of soils, and the leaching of chelating agents may cause groundwater contamination and increase the cost of phytoextraction (Almaroai *et al.*, 2012). Additionally, in studies involving *Salix*, *Thlaspi* and *Arabidopsis*, chemical treatments have not significantly increased the uptake of Cd, and the application of EDTA has decreased both biomass yield and shoot Cd concentration (McGrath *et al.*, 2006). The use of cultural cropping techniques may be an ideal method for strengthening phytoextraction by increasing plant biomass (Gonzaga *et al.*, 2008; Wei *et al.*, 2008). Repeated harvests are the most common method used to promote plant growth and obtain higher biomass (Hamlin and Barker, 2006). Ji *et al.* (2011) showed that double harvesting significantly enhanced shoot biomass and Cd extraction by *Solanum nigrum* in Cd-contaminated agricultural soils.

In this study, six forage species were used: chicory (*Cichorium intybus*), amaranth (*Amaranthus hypochondriacus*), Rumex K-1 (*Rumex patientia* × *R. tianschanicus*), alfalfa (*M. sativa*), sweet sorghum (*Sofrghum bicolor*) and sudangrass (*Sorghum sudanese*). The main objective of this research was to compare the efficiency of the six forage species in their phytoextraction of Pb, Cd and Zn from contaminated soil under different harvesting strategies (double harvesting or single harvesting).

MATERIALS AND METHODS

Site description

A field experiment was performed in Danshan Township, Shangyu City, Zhejiang Province, China (29° 59′ 54.08″ N, 120° 46′ 48.47″ E). The climate at the site is subtropical monsoon with an average annual temperature of 15.0–18.0 °C and annual rainfall of 1 400 mm. The soil contamination has been caused by long-term irrigation with local heavy metal-contaminated water. Soil physicochemical properties were measured at the beginning of the experiment (before planting), and selected soil properties and metal concentrations are shown in Table I. The Zn content is 1.42 times the corresponding background content in the soils of Zhejiang Province, and the contents of Cd and Pb are significantly higher than the maximum heavy metal amounts (Cd: 0.4 mg kg^{-1}; Pb: 50 mg kg^{-1}) allowed under the China Environmental Quality Standard for Soils (GB15618-2008, Grade II).

Experimental design

The experiment used a six (forage species) × two (harvesting strategies) factorial design arranged in a randomized complete block, split plot design with four replicates. The main plot and subplot factors were forage species and cultivation method, respectively. The six forage species were chicory, amaranth, Rumex K-1, alfalfa, sweet sorghum and sudangrass, which are commonly grown for forage in southern China. The cultivation methods used were double harvesting, in which the first crop was harvested 60 d after sowing and the second crop was harvested 120 d after sowing, and single harvesting, in which harvesting occurred 120 d after sowing.

The seeds of all crops were sterilized in 2% (volume:volume) hydrogen peroxide for 10 min, washed several times with tap water and soaked in water overnight. The soaked seeds were sown directly in the designated field plots on May 8, 2011. The main plot areas were trimmed to 2.0 m × 2.0 m, and seeding density was 25 plants m^{-2}. To prevent emergence failure, more seeds were sown in each hole than the number of plants required for the experiment, and 10 d after sowing, the seedlings were thinned to one plant per hole. Prior to sowing, the soil was fertilized with N:P:K (1:1:1) fertilizer, which was applied at the rate of 75 kg N ha^{-1}. During the experimental period, the field plots were watered, and weeds were removed manually when necessary; no pesticides were used.

Under double harvesting, 50 plants (2 m^2) were mowed by hand in the first crop to a stubble height of 1.0 m for the three tall crops (sweet sorghum, sudangrass and amaranth) and to 0.25 m for the three low-growing crops (Rumex K-1, chicory and alfalfa) 60 d

TABLE I

Selected chemical properties of the soil in the study field

pH	Total							Extractable		
	Organic matter	N	P	K	Cd	Pb	Zn	Cd	Pb	Zn
	g kg^{-1}				mg kg^{-1}					
7.10	303	1.26	0.91	3.07	4.52	721	96.74	1.02	115	11.20