Science of the Total Environment 408 (2010) 3469–3476

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Potential for phytoextraction of PCBs from contaminated soils using weeds

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ARTICLE INFO

Article history:
Received 14 January 2010
Received in revised form 15 April 2010
Accepted 16 April 2010
Available online 18 May 2010

Keywords:
Polychlorinated biphenyls
Phytoextraction
Weed species
Contaminated soils
Field sites
Phytoremediation

ABSTRACT

A comprehensive investigation of the potential of twenty-seven different species of weeds to phytoextract polychlorinated biphenyls (PCBs) from contaminated soil was conducted at two field sites (Etobicoke and Lindsay) in southern Ontario, Canada. Soil concentrations were 31 μg/g and 4.7 μg/g at each site respectively. All species accumulated PCBs in their root and shoot tissues. Mean shoot concentrations at the two sites ranged from 0.42 μg/g for *Chenopodium album* to 35 μg/g for *Vicia cracca* (dry weight). Bioaccumulation factors ($BAF = [PCB]_{plant\ tissue}/[PCB]_{mean\ soil}$) at the two sites ranged from 0.08 for *Cirsium vulgare* to 1.1 for *V. cracca*. Maximum shoot extractions were 420 μg for *Solidago canadensis* at the Etobicoke site, and 120 μg for *Chrysanthemum leucanthemum* at the Lindsay site. When plant density was taken into account with a theoretical density value, seventeen species appeared to be able to extract a similar or greater quantity of PCBs into the shoot tissue than pumpkins (*Curcurbita pepo* ssp. *pepo*) which are known PCB accumulators. Therefore, some of these weed species are promising candidates for future phytoremediation studies.

1. Introduction

Polychlorinated biphenyls (PCBs) are a group of persistent organic contaminants that were mass produced and released into the environment either inadvertently through spills or by poor disposal practices (ATSDR, 2000). Despite an almost worldwide ban on PCBs since the late 1970s, PCB contamination is still found today in soils throughout the world (ATSDR, 2000; Puri et al., 1997). In Canada, any soil above 50 μg/g PCBs must be destroyed (i.e. incinerated) or properly stored in a registered facility (Canada Gazette, 2008), while a soil quality guideline of 33 μg/g for commercial or industrial soils is recommended by the Canadian Council of Ministers of the Environment (CCME, 1999). As current disposal strategies such as incineration are expensive and destroy the soil matrix, more environmentally-friendly remediation techniques are clearly needed (Ghosh and Singh, 2005).

Phytoextraction is a subcategory of phytoremediation, in which plants take contaminants (generally metals) into their roots from the soil, and then translocate them into above ground plant tissues for storage (Cherian and Oliveira, 2005; Porębska and Ostrowska, 1999). Plants are then harvested, composted to reduce biomass and concentrate the contaminants, and finally incinerated or placed in a secure hazardous waste site (Macek et al., 2000; Reddy and Michel, 1998; Sas-Nowosielska et al., 2004).

To date, most research on organic contaminants has focused on phytodegradation or phytotransformation with limited research using phytoextraction (Aken et al., 2010; Cherian and Oliveira, 2005). Research investigating phytoextraction of organic contaminants has mainly focused on food crops, with members of the *Cucurbita* genus known to extract chlordane (e.g. Mattina et al., 2007), DDT (e.g. Lunney et al., 2004), dieldrin and endrin (e.g. Otani and Seike, 2006), dioxins and furans (Hülster and Marschner, 1994), and PCBs (e.g. Zeeb et al., 2006) from soil. Studies further demonstrated that pumpkins (*Cucurbita pepo* ssp. *pepo*) grown *in situ* were able to actively take up PCBs from the soil ($[PCB]_{soil} = 46$ μg/g at the first site and 5.6 μg/g at the second site respectively) into the roots and translocate them into the shoot tissues. The corresponding $[PCB]_{shoot}$ were 6.7 μg/g at the first site, and 7.3 μg/g at the second site (Low et al., 2009b; Whitfield Åslund et al. 2007).

When assessing plants to determine their potential as phytoremediators, factors to consider include, i) the contaminant type, availability and concentration in the soil, ii) the ability of the plant to transport the contaminant from the soil into different tissues, and iii) the plant biomass production in a given area and within a given time period (Anderson et al., 1993; Porębska and Ostrowska, 1999).

For phytoextraction to be an effective remediation strategy, it is necessary to maximize the contaminant concentration in the shoot tissues so as to minimize harvesting and processing costs. Bioaccumulation factors ($BAFs = [PCB]_{plant\ tissue}/[PCB]_{mean\ soil}$) are used to determine the ratio of the PCB concentration in the plant tissue compared to the PCB concentration in the soil, while translocation factors ($TLFs = BAF_{shoot}/BAF_{root}$) are used to determine the ratio of PCBs transferred from the root into the shoot.

Ideally, both shoot BAFs and TLFs should be greater than one. To date, average shoot BAFs of 0.06 (Low, 2009a; Zeeb et al., 2006), 0.12

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0048-9697/$ – see front matter.
doi:10.1016/j.scitotenv.2010.04.036

(Whitfield Åslund et al. 2007), 0.42 and 0.53 (Whitfield Åslund et al., 2008) have been recorded for whole or partial pumpkin shoots, while White et al. (2006) noted a BAF of 0.21 for *C. pepo* ssp. *pepo* (zucchini) plants. BAFs ranging from 0.0004 for soybeans to 0.45 for common sedge, and <0.30 for seven other species were observed by Zeeb et al. (2006).

Ongoing research has begun to show that weed species may play an important role in the phytoremediation of organic and inorganic contaminants (Cunningham and Ow, 1996; Kopf-Johnson, 2006; Porębska and Ostrowska, 1999). Advantages of weeds for phytoremediation are that they are easy to cultivate and propagate, generally self-sustainable, relatively inexpensive, and are often hardier than many cultivated species. As there are thousands of physiologically different species with unique root systems and exudates, growth patterns, stems, and leaves, it is anticipated that these diverse characteristics will allow remediation of a variety of contaminants. Furthermore, many weeds are perennial species, which may prove to be advantageous for phytoremediation by stabilizing, extracting, or degrading contaminants for longer time periods in a given year, and over several years. Lastly, weeds are particularly adept at growing in inhospitable or disturbed locations, and may be able to tolerate and thrive in areas of high contamination (Cunningham and Ow, 1996; Ligenfelter and Hartwig, 2007).

To date, removal of organic contaminants by phytoextraction has only been documented for a few weed species. Bush et al. (1986) showed that *Lythrum salicaria* leaves accumulated 210 ng/g PCBs by systemic transport with limited scavenging of PCBs from air. Likewise, a preliminary study by Kopf-Johnson (2006) indicated that six weed species were able to accumulate PCBs in their shoots (0.7–13.7 μg/g). Singh and Jain (2003) also demonstrated that *Ambrosia artemisiifolia*, an *Amaranthus* species, and *Solidago canadensis* were able to remove the organics trinitrotoluene and hexahydro-1,3,4-trinitro-1,3,5-triazine from soil.

The current study presents a comprehensive investigation of the uptake potential of twenty-seven different species of weeds that were observed growing naturally at two PCB-contaminated field sites in southern Ontario between 2005 and 2008. As pumpkins are known PCB extractors, weed root and shoot concentrations, bioaccumulation factors, and total shoot extractions were calculated and compared to those of pumpkins to identify promising weed species for the remediation of PCB-contaminated soil.

2. Materials and methods

2.1. Site descriptions and soil preparation

The Schneider Electric site is a former transformer manufacturing facility located in Etobicoke, Ontario, Canada. Soil at this site is contaminated with a mixture of Aroclors 1254/1260, with a mean soil concentration of 31 μg/g (range: 0.60–260 μg/g). Soil was classified as a coarse grain sandy soil with a total organic carbon content of 3.5%, and pH 7.1 (Whitfield Åslund et al. 2007; 2008). An asphalt cap covers the contaminated area, except for a 25 m by 7 m plot where the cap was removed in 2004. Groundwater flowing through the contaminated area is collected and treated for PCBs on-site by a water treatment facility before being released back into the municipal sewage system.

The second field site is located in Lindsay, Ontario, Canada, where a former major chemical company used PCB-containing oil as a heat transfer medium during production of food-grade casings and polyethylene films. Soil at this site is contaminated with Aroclor 1248, with a mean soil concentration of 4.7 μg/g (range: 0.50–23 μg/g). The soil is predominantly clay, with 4.3% total organic carbon (Low et al., 2009b). A 12 m by 12 m plot was created in 2006 for the purpose of experimental phytoremediation studies.

Both sites are surrounded by a 2 m high chain-link fence to prevent access by unauthorized personnel. At the start of each growing season, soil samples were collected (0–30 cm depth) as described in Whitfield Åslund et al. (2007).

2.2. Site establishment and maintenance

A 30 cm wide border was left unplanted around the perimeter of both field sites and allowed to be naturally colonized by seeds in the soil or by those blown onto the site. In 2008, areas in the middle of the Etobicoke and Lindsay sites (14 m^2 and 12 m^2 respectively) were also left unplanted to allow for colonization by weeds. All plants were identified according to Ontario Weeds (OMAFRA, 2001) and Weeds of Canada and the Northern United States (Royer and Dickinson, 2006). Plants were photographed and monitored on a weekly basis for general health.

2.3. Sample collection

Twenty-seven weed species ($n = 2$–6 per species) were harvested by loosening the soil around the roots and shaking off excess soil. Plants were separated into root and shoot tissues using scissors, which were rinsed with methanol between cuts. As no PCBs were detected during air monitoring at the Etobicoke site (Whitfield Åslund et al. 2007), aerial deposition of PCBs on plant tissues was considered negligible. Plant tissues were washed on-site under running water, blotted dry, and weighed to the nearest hundredth of a gram. Plant tissues were placed in individually labelled Whirlpak® or Ziplock® bags and kept frozen at the Analytical Services Unit at Queen's University until analysis.

2.4. Sample selection for analysis

Whole plants for each species were harvested in triplicate between 2005 and 2008 (exceptions noted in Supporting Information (SI)). Representative subsamples were prepared from root or shoot tissues when the whole sample was too large for complete analysis (i.e. wet masses >30 g). When the total tissue biomass was >30 g but <50 g, the whole sample was chopped and homogenized, and then a subsample (~10–15 g) was selected for analysis. When the total tissue biomass was >50 g, a representative subsection of the whole plant was chopped and homogenized, and then a subsample (~10–15 g) was selected for analysis. Subsamples were dried prior to analysis, and used to estimate the PCB concentration in the whole plant tissue. The total dry mass of the plant was determined by applying the dry/wet factor from the subsampled tissues to the total wet biomass.

2.5. Analysis of PCB Aroclors in soil and plant samples

Analytical procedures were based on the methods described in Whitfield Åslund et al. (2007). Briefly, plant samples were finely chopped with scissors. Soil and plant samples were dried overnight in a vented oven at 25 °C for approximately 12–18 h, and then ground with sodium sulphate and Ottawa sand. Decachlorobiphenyl (DCBP) was used as an internal surrogate standard. All samples were extracted using a soxhlet apparatus with dichloromethane as the solvent, concentrated with a rotoevaporator to ~2 mL, and solvent exchanged for hexanes by adding three ~5.0 mL aliquots of hexane to the sample and rotoevaporating off the solvent. Samples were analyzed for total PCBs (Aroclor 1248 or Aroclors 1254/1260, μg/g dry weight) using an Agilent 6890 Plus gas chromatograph with a ^{63}Ni electron capture detector (GC/ECD), and HPChem station software. Roots and shoots were analyzed separately ($n = \sim 3$), and an average value was calculated to estimate the PCB concentration in each tissue for all species.

2.6. Quality assurance/quality control (QA/QC)

One blank, one control, and one analytical duplicate sample were prepared and analyzed for every nine samples. The control sample