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Potential for phytoextraction of PCBs from contaminated soils using weeds

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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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(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

was spiked with 5.0 µg/g of an appropriate Aroclor standard (1248/1254/1260), with a mean recovery of 84%. Analytical blanks were all less than 0.10 µg/g (the detection limit), and the mean relative standard deviation between the analytical duplicate samples was 14%. All data are reported to two significant figures.

2.7. Statistical analyses

All PCB concentrations (soil and tissue samples) are reported on a dry-weight basis. The data analyzed by ANOVA were tested for normality (Kolmogorov–Smirnov test), and transformed with the natural logarithm ($\log_e$) to increase normality of the data set for both sites.

One-way analysis of variance (ANOVA) was used to compare differences in shoot concentrations and shoot extractions between each species at each site respectively (factor: plant species), and to analyze the difference in shoot extractions between sites (factor: site). All other analyses of the concentrations and BAFs were conducted using a two-way ANOVA, followed by a post hoc Tukey test if differences were detected (factors: site and tissue). A separate two-way ANOVA was conducted to compare the shoot BAFs for six plant species common to both sites. A significance level of $\alpha = 0.05$ was used for all tests, and results were recorded with the standard error of the mean. All statistical analysis was conducted using Systat 13.0™.

3. Results

3.1. PCB concentrations in soil

Mean PCB soil concentrations of 31 µg/g ($n = 89$; range: 0.60–260 µg/g) and 4.7 µg/g ($n = 46$; range: 0.50–23 µg/g) were calculated based on soil samples collected from 2004 to 2006 at the Etobicoke site and from 2006 to 2007 at the Lindsay site, respectively. Soil concentrations at the Etobicoke site were significantly greater than those at the Lindsay site.

3.2. PCBs concentrations in plants

Mean root concentrations ranged from 4.7 µg/g (*L. salicaria*) to 310 µg/g (*Brassica nigra*) at the Etobicoke site, and from 2.5 µg/g (*Rumex crispus*) to 47 µg/g (*Solanum nigrum*) at the Lindsay site (see SI). Mean shoot concentrations ranged from 2.3 µg/g (*Polygonum persicaria*) to 35 µg/g (*V. cracca*) at the Etobicoke site and from 0.42 µg/g (*C. album*) to 4.8 µg/g (*P. persicaria*) at the Lindsay site (Fig. 1). Root and shoot concentrations were both significantly greater

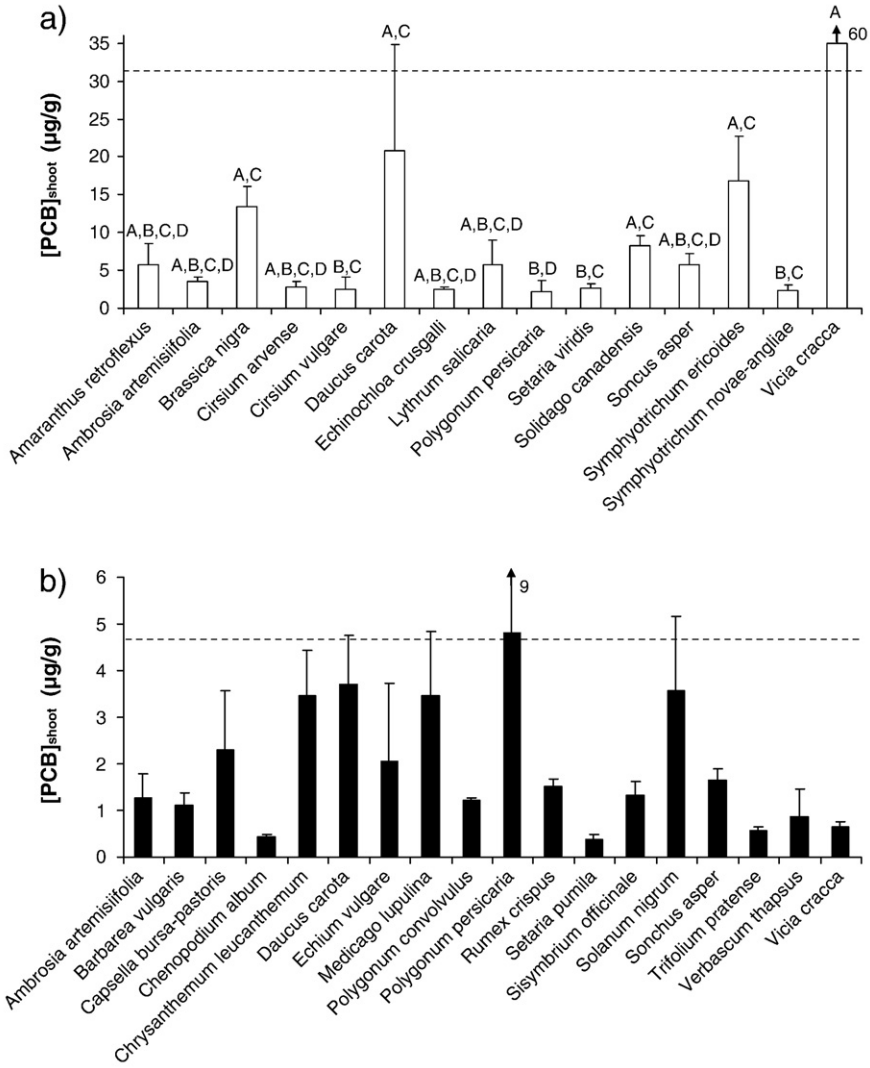

Fig. 1. Mean shoot concentrations for weeds at a) the Etobicoke site, and b) the Lindsay site. Soil concentrations were 31 µg/g and 4.7 µg/g respectively, as shown by the dotted lines. Error bars reported as the standard error of the mean. A one-way ANOVA was used to compare $\log_e[PCB]_{shoot}$ between species at each site respectively. Letters indicate significant differences between plant species ($p < 0.05$).

at the Etobicoke site compared to the Lindsay site. Considerable variation was observed between tissue concentrations in replicate plants for some species.

3.3. Bioaccumulation and translocation factors

Mean root BAFs ranged from 0.15 (*L. salicaria*) to 9.9 (*B. nigra*) at the Etobicoke site, and from 0.54 (*R. crispus*) to 10 (*S. nigrum*) at the Lindsay site. Root BAFs were not significantly different between the two sites. In comparison, mean shoot BAFs were significantly higher at the Lindsay site (range 0.08 to 1.1 at the Etobicoke site and 0.08 to 1.0 at the Lindsay site). However, when the shoot BAFs of six species of weeds common to both sites were directly compared (e.g. *P. persicaria* from Etobicoke versus *P. persicaria* from Lindsay), none of the shoot BAFs were significantly different (Fig. 2).

TLF values ranged from 0.04 (*B. nigra*) to 1.9 (*D. carota*), and from 0.07 (*P. convolvulus*) to 0.90 (*R. crispus*) at the Etobicoke and Lindsay sites, respectively (see SI).

3.4. PCB extraction

The mean total quantity of PCBs extracted per plant was calculated for both roots and shoots (extraction (μg per plant) = $[PCB]_{plant\ tissue}$ (μg/g) × dry mass of plant (g)). Mean root extractions per plant ranged from 18 μg (*Echinochloa crusgalli*) to 1100 μg (*S. canadensis*) at the Etobicoke site, and from 1.4 μg (*Setaria pumila*) to 83 μg (*Daucus carota*) at the Lindsay site. Mean shoot extractions ranged from 3.5 μg (*S. pumila*) to 420 μg (*S. canadensis*) at the Etobicoke site, and from 2.9 μg (*S. pumila*) to 120 μg (*C. leucanthemum*) at the Lindsay site (Fig. 3). Shoot extractions were not significantly different between the two sites.

4. Discussion

4.1. Plant health and weed designation

While the PCB concentrations in this study are not considered phytotoxic to plants (Weber and Mrozek, 1979; Zeeb et al., 2006), minimal soil quality may have affected plant growth. However, many weeds have shown the ability to adapt to poor growing conditions (Cunningham and Ow, 1996; Ligenfelter and Hartwig, 2007). Hence it is not surprising that all species investigated appeared to thrive on these industrial PCB-contaminated soils, with various species completing their normal life cycles by producing seeds (e.g. *Amaranthus retroflexus*, *A. artemisiifolia*) or spreading rhizomes (e.g. *S. canadensis*, *V. cracca*).

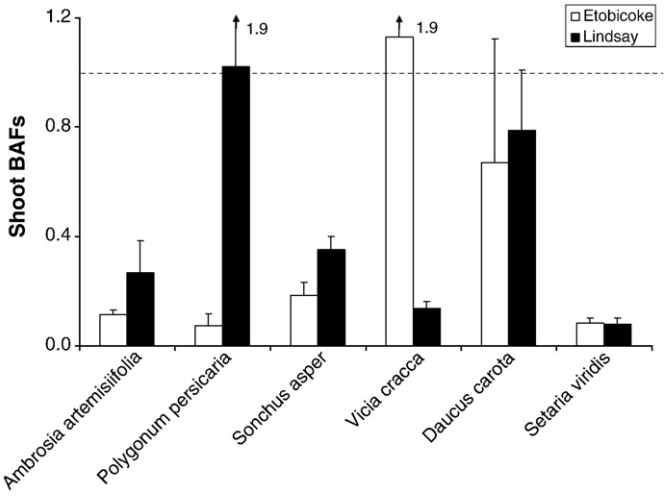

Fig. 2. Comparison of shoot BAFs between weeds at the Etobicoke and the Lindsay sites. Error bars reported as the standard error of the mean, while the 1:1 ratio line is shown as a dashed line. A two-way ANOVA comparing $\log_e BAF_{shoot}$ for each species determined that there was not significant difference between any of the sets of species common to both sites.

For this study, all naturally-growing weed species were harvested and analyzed for their ability to accumulate PCBs. Some species are legally classified as being noxious weeds in certain regions; hence the official designation of each species in each location should be taken into consideration when determining which ones are useful for local phytoremediation projects.

4.2. PCB concentrations

Since soil heterogeneity is common at naturally-weathered contaminated sites, numerous soil samples were collected and analyzed from both surface (0–10 cm) and depth (0–30 cm) over numerous years to help characterize the mean soil concentration. Mean soil concentration was not significantly different between years (Whitfield Åslund et al., 2008). As plant roots grow in many directions, they will access a wide range of contaminant concentrations as they do not remain in one location. Thus the mean soil concentration was chosen as the best indicator of rhizosphere conditions. Similar to observations by Zeeb et al. (2006), plants grown in soil with higher PCB concentrations (Etobicoke) had higher root and shoot PCB concentrations compared to plants grown in soil with lower PCB concentrations (Lindsay).

As pumpkins, *C. pepo* ssp. *pepo*, are known PCB-extractors, weed shoot concentrations were compared to pumpkins grown either at the Etobicoke or at the Lindsay site. Five species from the Etobicoke site exceeded the pumpkin shoot concentration (6.7 μg/g), while no species exceeded the Lindsay site pumpkin shoot concentration (7.3 μg/g). Thus numerous weed species were shown to accumulate similar or larger shoot concentrations than pumpkins.

In some of the weed species (e.g. *Daucus carota* and *Viccia cracca*), the variations in the PCB tissue concentration were very high as compared to other weed species (e.g. *Chrysantheum leucanthemum* and *Echium vulgare*) and pumpkins (Low, 2009a). This may be due to plant variability inherent in these species. Plants are also strongly influenced by local environmental conditions; roots grow in soil in search of nutrients and water, while variations in temperature, precipitation, and amount of light further affect tissue growth (Hinsinger, 1998; Huner et al., 1998). Since most contaminants have no nutritional value, contaminant uptake is believed to be an inadvertent process for most plants. Thus various environmental factors likely influence the uptake and accumulation of contaminants in plant tissues, with plant age, growth stage and soil properties known to play an important role in plant uptake of metals (Boyd et al., 1999; Jung, 2008; Sharma et al., 2007). In this study, individual plants from each species were harvested when they were present throughout the four-year sampling period. During this time, variations in environmental conditions such as precipitation and temperature likely affected plant growth, and thus potentially the plant tissue concentrations. The variation in these results highlights the necessity of conducting field research rather than just controlled experiments inside a greenhouse, as this range in uptake reflects the complexity of issues that researchers and site remediators face when working with plants grown in naturally contaminated soils.

4.3. Bioaccumulation factors and translocation factors

The main objective of phytoextraction is to maximize the PCB concentration in the shoot tissue so as to minimize harvesting and processing costs. At present, few PCB-extractors achieve BAFs or TLFs ≥ 1 (Whitfield Åslund et al., 2007; 2008; Zeeb et al., 2006). In this study, only *V. cracca* at the Etobicoke site, and *P. persicaria* at the Lindsay site achieved shoot BAFs >1, while only *L. salicaria* from the

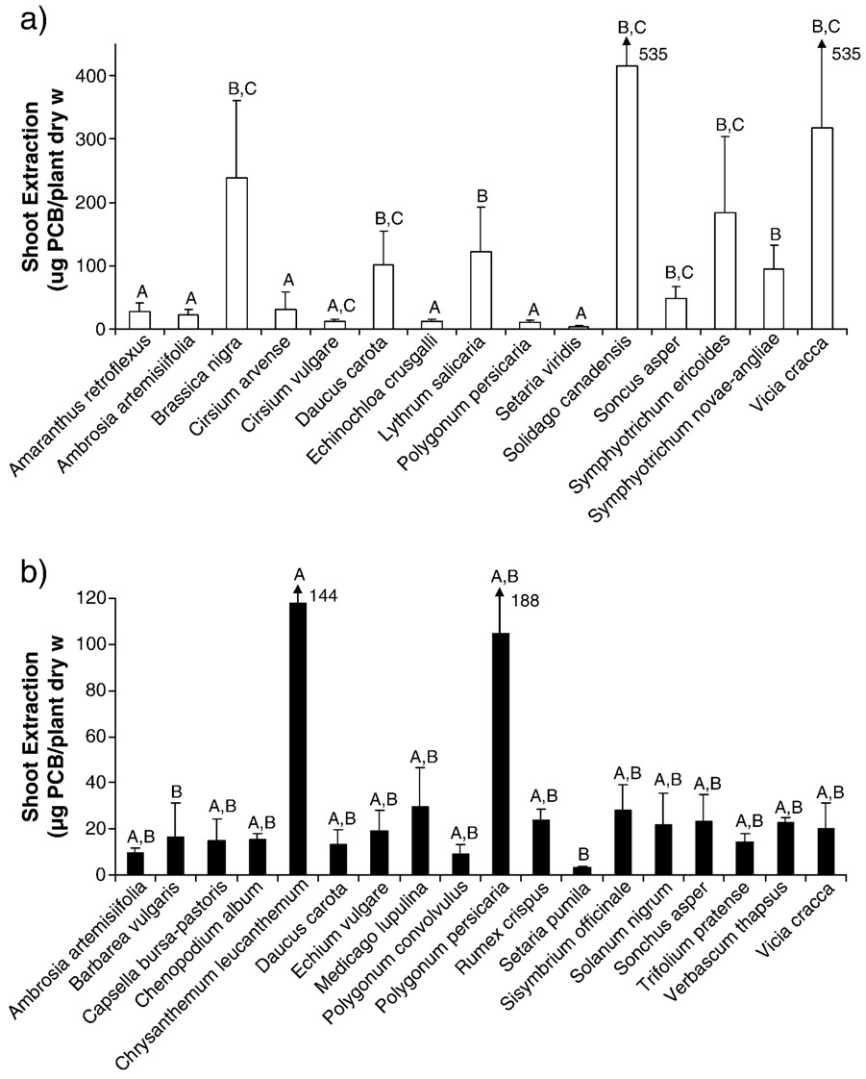

Fig. 3. Total mean shoot extraction per plant species at a) the Etobicoke site, and b) the Lindsay site. Error bars reported as the standard error of the mean. A one-way ANOVA was used to compare $\log_e \text{Extraction}_{\text{shoot}}$ between species at each site respectively. Letters indicate significant differences between plant species ($p<0.05$).

Etobicoke site achieved a TLF >1. However, *D. carota* and *S. ericoides* from the Etobicoke site, and *Capsella bursa-pastoris*, *C. leucanthemum*, *D. carota*, *Medicago lupulina*, and *S. nigrum* from the Lindsay site all had shoot BAFs ≥0.50, while *A. retroflexus*, *Cirsium arvense*, *D. carota*, and *S. asper* from the Etobicoke site, and *C. leucanthemum*, *Echium vulgare*, and *R. crispus* from the Lindsay site all had TLFs ≥0.50 (SI). *D. carota* from the Etobicoke site, and *C. leucanthemum* from the Lindsay site were the only two species to have both a shoot BAF and a TLF ≥0.50.

When choosing promising species for phytoremediation studies, BAFs are a useful tool for comparing the uptake of different Aroclors from different soil types and concentrations, by different species. Based on the congener composition of the three Aroclors, it was predicted that BAFs would be higher at the Lindsay site. Aroclor 1248 is composed of a larger percentage of lower chlorinated congeners than either Aroclor 1254 or 1260, with lower K_{ow} values, indicating that it is more soluble in water and less likely to sorb as strongly to soil particles (Mackay et al., 2006). Soil properties including type and organic carbon content may also have affected PCB uptake, as PCBs are more likely to sorb to soil with a higher organic carbon content and a smaller particle size (e.g. clay).

This study demonstrated that numerous weed species can achieve similar or greater shoot BAFs than those documented by other PCB-extracting species, where BAFs ranged from 0.06 to 0.53 (Low, 2009a; White et al., 2006; Whitfield Åslund et al., 2007; 2008; Zeeb et al., 2006). It also appears that the shoot BAFs in this study are more dependent on species than on the Aroclor, or soil type or concentration, as all six weed species common to both sites did not have significantly different shoot BAFs. Variation in BAFs between individual plants and between species is likely due to differences in plant growth patterns and overall age and size, year of harvest, environmental factors (e.g. temperature, precipitation, photoperiod, and soil properties including organic carbon content, soil pH, and nutrient levels), water absorption, structure and size of roots, and root exudate composition.

4.4. Application of theoretical density values/m² to optimize total extraction

To optimize the phytoextraction of PCBs, it is important to maximize the quantity of PCBs removed by the shoot tissue. In this study, dry shoot biomass ranged from 34 to 99% of the total dry plant biomass, and up to 110 g dry weight. The average shoot to root ratio across all plants was 5:1, which is within the range reported by Gier (1940) for field tobacco plants (5:1 to 13:1), where variations were due to environmental conditions and cultivation practices. A plant with a low PCB concentration may still extract a significant quantity of PCBs given a large shoot biomass.

Direct comparison between weeds and pumpkin plants of the total quantity of PCBs extracted on a per-plant-basis underestimates the potential of weeds to extract PCBs, due to the significant difference in

Table 1
Mean shoot dry weight, estimated plant densities and mean total shoot extraction per square metre for a) plants common to both sites, b) plants only at the Etobicoke site and c) plants only at the Lindsay site, respectively. Mean pumpkin extractions per square metre at the Etobicoke site (Whitfield Åslund et al., 2007) and at the Lindsay site (Low et al., 2009b) were included for comparison. Values in bold are calculated extractions that are ≥pumpkin extraction values.

Plant Species	Site	*n*	Mean dry wt/plant (g)	Density/m^2 [a]	PCB extraction/m^2 [b]	Source
a)						
Ambrosia artemisiifolia	Etobicoke	7	6.1	37	810	Clay et al., 2006
				77	**1700**	Payne et al., 2008
				270	**5900**	Thomas and Bazzaz, 1996
				630	**14,000**	Fumanal et al., 2005
	Lindsay	4	17	37	350	Clay et al., 2006
				77	720	Payne et al., 2008
				270	**2500**	Thomas and Bazzaz, 1996
				630	**5900**	Fumanal et al., 2005
Daucus carota	Etobicoke	3	10	17	**1700**	Pill et al., 1994
	Lindsay	3	3.4	17	230	Pill et al., 1994
Polygonum persicaria	Etobicoke	5	9.4	400	**4100**	Griffith and Sultan, 2006
	Lindsay	3	28	400	**42,000**	Griffith and Sultan, 2006
Setaria pumila	Etobicoke	6	3.8	500	**1800**	Canola Council of Canada (CCC), 2003[c],
	Lindsay	3	8.0	500	1500	CCC, 2003[c]
Sonchus asper	Etobicoke	4	8.1	20	950	CCC, 2003
				65	**1800**	Getting and Potter, 2000
	Lindsay	6	17	20	460	CCC, 2003
				65	**1500**	Getting and Potter, 2000
Vicia cracca	Etobicoke	3	9.9	5	**1600**	Seymour, 2005[d]
	Lindsay	2	33	5	100	Seymour, 2005[d]
Pumpkin	Etobicoke		3	1	**1500**	OMAFRA, 2000
	Lindsay		3	1	**2100**	OMAFRA, 2000
c—Density for *Setaria viridis* d—Density for *Vicia sativa*						
b)						
Amaranthus retroflexus		4	13	19	510	Hajyieva and Soroka, 2008
Brassica nigra		3	16	100	**2400**	MAFRI, 2004b[c]
Cirsium arvense		4	2.2	12	370	Barstatis and Sieg, 2003
				40	1250	CCC, 2003
Cirsium vulgare		3	8.2	42	470	Randall and Rejmánek, 1993
Echinochloa crusgalli		3	3.6	19	210	Hajvieva, 2008
				200	**2200**	Zimdahl, 2004
Lythrum salicaria		3	47	2	250	Gilbert and Parisien, 1989
Solidago canadensis		5	62	10	**4200**	Zhang et al., 2009
Symphyotrichum ericoides		2	12	35	**6400**	Rice and Stritzke, 1989
Symphyotrichum novae-angliae		3	38	144	**14,000**	USDA, 2003
Pumpkins		3		1	**1500**	OMAFRA, 2000
c—Density for *Brassica oleracea*						
c)						
Barbarea vulgaris		4	10	38	620	Ausmane et al., 2008
Capsella bursa-pastoris		3	6.0	400	**6000**	Sulev, 2009
Chenopodium album		3	37	19	300	Hajyieva and Soroka, 2008
				43	670	Getting and Potter, 2000
				170	**2700**	Zimdahl, 2004
				200	**3100**	MAFRI, 2004a
Chrysanthemum leucanthemum		3	48	20	**2400**	Pill et al., 1994
Echium vulgare		3	20	20	380	KlinKhamer and de Jong, 1990
Medicago lupulina		3	6.8	40	1200	Hogenbirk and Reader, 1989
Polygonum convolvulus		3	7.2	9	80.	Zollinger et al., 2003
				11	98	McGinely and Tilman, 1993
Rumex crispus		3	16	21	500	Dimitrova and Marinov-Serafimov, 2008
				270	**6500**	Thomas and Bazzaz, 1996
Sisymbrium officinale		3	28	190	**5300**	Merkel et al., 2004[c]
Solanum nigrum		3	22	120	**2500**	Getting and Potter, 2000
Trifolium pratense		3	25	8000	**110,000**	Black, 1960
Verbascum thapsus		2	35	44	990	Barstatis and Sieg, 2003
Pumpkins		3		1	**2100**	OMAFRA, 2000
c—Density for *Sisymbrium loeselii* L.						

[a] —In one case, a density value for a similar species was used when a factor was not available for a particular species. The alternative species is footnoted under source.
[b] Any plant with an extraction/m^2 over 2100 μg is bolded for comparison to the mean pumpkin shoot extraction/m^2 from the Lindsay site.

total biomass of each plant. Average pumpkin wet weight per plant is ~5 kg per plant, with an average extraction of 1500 μg at the Etobicoke site (Whitfield Åslund et al., 2007) and 2100 μg at the Lindsay site (Low et al., 2009b). In comparison, the largest weeds (e.g. *S. canadensis*) were at most 0.4–0.5 kg per plant, with a maximum extraction of 420 μg of PCBs. Only five weed species at the Etobicoke site and two at the Lindsay site extracted more than 100 μg of PCBs on a per-plant-basis.

Whitfield Åslund et al. (2008) demonstrated that the optimal planting density for maximum shoot biomass and shoot concentration in pumpkins is one plant per square metre. In comparison, many weeds naturally grow at much higher densities, indicating that the extraction per plant will under-represent the potential of many of these species. Theoretical density values per square metre for each weed species were gleaned from the literature and applied to the total extraction per plant for each species, to obtain the total mean extraction per square metre (total extraction/m^2 = density of plant/m^2 × total extraction/plant) (Table 1). As different authors recorded densities for different purposes (e.g. maximum planting, density in field crops), and at different stages of growth (e.g. seedlings, mature plants), a range of densities were obtained for several species from different sources. For the purpose of this investigation, the maximum density value obtained from the literature was assumed to be the optimal density. Thus inclusion of a theoretical density factor based on the growth area of one square metre for each weed species normalizes the difference in biomass between species, allowing for a better comparison with pumpkins. The use of a density value increased the total potential extraction of ten species from the Etobicoke site to 1500 μg or greater per square metre, and nine species from the Lindsay site to 2100 μg or greater per square metre, indicating that many weed species could potentially extract a similar or larger quantity of PCBs than pumpkins per square metre. In addition, many weeds have a longer growing season per year, and are less affected by adverse environmental conditions.

Further research using monoculture plots of weeds is required to optimize the uptake of PCBs by various species at different densities and at different phases in their growth cycles, as there was significant variation in concentrations, BAFs and extractions, even within each species. Controlled experiments in the greenhouse using plant species identified in this study will also help deduce which environmental factors strongly affect the uptake of PCBs from contaminated soil, and will help determine the relationship between plant density, total biomass, and total extraction/m^2 for each weed species.

Parameters to investigate include determining if BAFs are always species-specific and how different species extract contaminants from soil. Of the weed species investigated, *C. leucanthemum*, *D. carota*, *P. persicaria*, *S. canadensis*, and *V. cracca* show strong potential to phytoextract PCBs in future, based on tissue concentrations, bioaccumulation factors and total extractions.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.scitotenv.2010.04.036.

References

Agency for Toxic Substances and Disease Registry (ATSDR). Toxicological profile for polychlorinated biphenyls (PCBs). Atlanta: Department of Health and Human Services, Public Health Service; 2000. p. 477–594. Available online: http://www.atsdr.cdc.gov/toxprofiles/tp17.html.

Aken BV, Correa PA, Schnoor JL. Phytoremediation of polychlorinated biphenyls: new trends and promises. Environ Sci Technol 2010;44:2767–76.

Anderson TA, Guthrie EA, Walton BT. Bioremediation. Environ Sci Technol 1993;27:2630–6.

Ausmane M, Gaile Z, Melngalvis I. The investigation of crop weediness in the crop rotation of organic farming system. Agronomijas Vēstis (Latvian Journal of Agronomy) 2008;10:25–31 ISSN 1691-3485.

Barstatis N, Sieg CH. Long-term response of two exotic plant species following a wildfire in the Black Hills, South Dakota. 2nd International Wildland Fire Ecology and Fire Management Congress. Poster Session 2, Fire Effects. Orlando, USA; 16–20 Nov 2003. Available online: http://www.fs.fed.us/ne/newtown_square/publications/other_publishers/OCR/ne_2003_bova001.pdf.

Black JN. An assessment of the role of planting density in competition between red clover (*Trifolium pratense* L.) and lucerne (*Medicago sativa* L.) in the early vegetative stage. Oikos 1960;11:26–42.

Boyd RS, Jaffré T, Odom JW. Variation in nickel content in the nickel-hyperaccumulating shrub *Psychotria douarrei* (Rubiaceae) from New Caledonia. Biotropica 1999;31:403–10.

Bush B, Shane LA, Wilson LR, Barnard EL, Barnes D. Uptake of polychlorobiphenyl congeners by purple loosestrife (*Lythrum salicaria*) on the banks of the Hudson River. Arch Environ Contam Toxicol 1986;15:285–90.

Canada Gazette. Part II. SOR/DORS/2008-273. 2008. 142:19. Available online: http://www.gazette.gc.ca/rp-pr/p2/2008/2008-09-17/pdf/g2-14219.pdf.

Canadian Council of Ministers of the Environment (CCME). Canadian soil quality guidelines for the protection of environmental and human health. Publication No. 1299; 2006. ISBN 1-896997-34-1.

Canola Council of Canada (CCC). Canola growers manual. Winnipeg: Direct Focus; 2003. Available online: http://www.canolacouncil.org/canola_growers_manual.aspx.

Cherian S, Oliveira M. Transgenic plants in phytoremediation: recent advances and new possibilities. Environ Sci Technol 2005;39(24):9377–90.

Clay SA, Kreutner B, Clay DE, Reese C, Kleinjan J, Forcella F. Spatial distribution, temporal stability, and yield loss estimates for annual grasses and common ragweed (*Ambrosia artimisiifolia*) in a corn/soybean production field over nine years. Weed Sci. 2006;54:380–90.

Cunningham SD, Ow DW. Promises and prospects of phytoremediation. Plant Physiol 1996;110:715–9.

Dimitrova T, Marinov-Serafimov P. Chemical control of curled dock (*Rumex crispus* L.) and other weeds in noncropped areas. Pesticidi i Fitomedicina (Pesticides and Phytomedicine) 2008;23:123–6, doi:10.2298/PIF0802123D.

Fumanal B, Chauvel B, Bretagnolle F. Demography of an allergenic European invasive plant: *Ambrosia artemisiifolia*. International Symposium on Plant Protection and Plant Health in Europe: Introduction and Spread of Invasive Species. Berlin, Germany; 9–11 Jun 2005. Available online: http://www.phytomedizin.org/filead-min/alte_Webseiten/Invasive_Symposium/articles/S6-08_Fumanal-044.pdf.

Getting JK, Potter BD. Effect of roundup formulations on weed control in soybeans at Lamberton, MN in 2000. University of Minnesota: Minnesota Agricultural Experiment Station; 2000. Available online: http://swroc.cfans.umn.edu/SWMNPEST/weed/roundup_beans.PDF.

Ghosh M, Singh SP. A review of phytoremediation of heavy metals and utilization of its byproducts. Applied Ecology and Environmental Research 2005;3:1-18.

Gier LJ. Root systems of bright belt tobacco. Amer Jour Bot 1940;27(9):780–7.

Gilbert J, Parisien R. Purple loosestrife control efforts of the Great Lakes Indian Fish and Wildlife Commission 1988–1989. Administrative Report 89-13. Odanah, WI: Great Lakes Indian Fish and Wildlife Commission; 1989. Available online: http://glifwc.org/biology/reports/PurpleLoosestrifeControlEfforts89-13.pdf.

Griffith TM, Sultan SE. Plastic and constant developmental traits contribute to adaptive differences in co-occurring *Polygonum* species. Oikos 2006;114:5-14.

Hajyieva H, Soroka S. Phytosanitary situation in sugar beet crops in Belarus. Zemdirbyste-Agriculture 2008;95:65–73 UDK 633.413:[632.51:632.6/.7](476). Available online: http://www.lzi.lt/tomai/95(3)tomas/95(3)tomas_65_73.pdf.

Hinsinger P. How do plant roots acquire mineral nutrients? Chemical processes involved in the rhizosphere. Adv Agron 1998;64:225–65.

Hogenbirk JC, Reader RJ. Biotic versus abiotic control of plant density: studies of *Medicago lupulina* L. on a topographic gradient. J Biogeogr 1989;16:269–77.

Hülster A, Marschner H. The influence of root exudates on the uptake of PCDD/PCDF by plants. Organohalogen Compound 1994;20:31–4.

Huner NPA, Öquist G, Sarhan F. Energy balance and acclimation to light and cold. Trends Plant Sci 1998;3(6):224–30.

Jung C. Heavy metal concentrations in soils and factors affecting metal uptake by plants in the vicinity of a Korean Cu–W mine. Sensors 2008;8:2413–23.

KlinKhamer PGL, de Jong TJ. Effects of plant size, plant density and sex differential nectar reward on pollinator visitation in the protandrous *Echium vulgare* (Boraginaceae). Oikos 1990;57:399–405.

Kopf-Johnson E. *In situ* phytoextraction of polychlorinated biphenyls (PCBs) by native weed species in Southern Ontario. 4th Year Honour Thesis. Kingston: Queen's University; 2006.

Ligenfelter DD, Hartwig NL. Introduction to weeds and herbicides. Pennsylvania State University: Publication Distribution Center; 2007. Available online: http://pubs.cas.psu.edu/freepubs/pdfs/uc175.pdf.

Low JE, Whitfield Åslund ML, Rutter A, Zeeb BA. Effect of plant age on PCB accumulation by *Curcurbita pepo* ssp. *pepo*. J Environ Qual 2009a;39:245–50.

Low JE, Whitfield Åslund ML, Rutter A, Zeeb BA. (submitted). The effects of pruning and nodal adventitious roots on PCB uptake by *Curcurbita pepo* grown in field conditions. (Submitted, December 2009b).
Lunney AI, Zeeb BA, Reimer KJ. Uptake of weathered DDT in vascular plants: potential for phytoremediation. Environ Sci Technol 2004;38:6147–54.
Macek T, Macková M, Káš J. Exploitation of plants for the removal of organics in environmental remediation. Biotechnol Adv 2000;18:23–34.
Mackay D, Shiu WY, Ma KC, Lee SC. Handbook of physical–chemical properties and environmental fate for organic chemicals. 2nd ed. Boca Raton: CRC Press; 2006.
Manitoba Agriculture, Food and Rural Initiatives (MAFRI). Lamb's quarters. Carmen, Canada: Crops Knowledge Centre; 2004a. Available online: http://www.gov.mb.ca/agriculture/crops/weeds/fab09s00.html.
MAFRI. Wild Mustard. Carmen, Canada: Crops Knowledge Centre; 2004b. Available online: http://www.gov.mb.ca/agriculture/crops/weeds/fab18s00.html.
Mattina MJI, Berger WA, Eitzer BD. Factors affecting the phytoaccumulation of weathered, soil-borne organic contaminants: analyses at the *ex Planta* and *in Planta* sides of the plant root. Plant Soil 2007;291:143–54.
McGinley MA, Tilman D. Short-term response of old-field plant communities to fire and disturbance. Am. Midl. Nat. 1993;129(2):409–13.
Merkel U, Rathke G-W, Schuster C, Warnstorff K, Diepenbrock W. Use of glufosinate-ammonium to control cruciferous weed species in glufosinate-resistant winter oilseed rape. Field Crop Res 2004;85:237–49.
Ontario Ministry of Agriculture Food and Rural Affairs (OMAFRA). Pumpkin and squash production. Toronto: Queen's Printer for Ontario; 2000. Available online: http://www.omafra.gov.on.ca/english/crops/facts/00-031.htm#spacing.
OMAFRA. Ontario weeds. In: Alex JF, editor. Publication 505. Guelph: Queen's Printer for Ontario; 2001.
Otani T, Seike N. Comparative effects of rootstock and scion on dieldrin and endrin uptake by grafted cucumber (*Cumis sativus*). J Pestic Sci 2006;31:316–21.
Payne KK, Riley EB, Wait JD, Bradley KW. Influence of spring and summer herbicide applications on weed control, total forage yield and total forage quality in tall fescue pastures in Missouri. Indianapolis, USA: North Central Weed Sci. Soc Abstr 63; 8–11 Dec 2008. p. 180. Available online: http://www.ncwss.org/proceed/2008/abstracts/180.pdf.
Pill WG, Smith WG, Frett JJ, Devenney D. Wildflower establishment in seedbeds created from an industrial co-product and co-composted municipal waste. J Environ Hortic 1994;12:193–7.
Porębska G, Ostrowska A. Heavy metal accumulation in wild plants: implications for phytoremediation. Polish Journal of Environmental Studies 1999;8:433–42.
Puri RK, Qiuping Y, Kapila S, Lower WR, Puri V. Plant uptake and metabolism of polychlorinated biphenyls (PCBs). In: Wang W, Gorsuch JW, Hughes JS, editors. Plants for environmental studies. Boca Raton: CRC Press; 1997. p. 481–513.
Randall JM, Rejmánek M. Interference of bull thistle (*Cirsium vulgare*) with growth of ponderosa pine (*Pinus ponderosa*) seedlings in a forest plantation. Can J Forest Res 1993;23:1507–13.
Reddy CA, Michel Jr FC. Fate of xenobiotics during composting. Proceedings of the 8th International Symposium on Microbial Ecology. Microbial biosystems: new frontiers. Canada: Halifax; 9–14 Aug 1998. Available online: http://plato.acadiau.ca/isme/Symposium15/reddy.PDF.
Rice CK, Stritzke JF. Effects of 2, 4-D and atrazine on degraded Oklahoma grasslands. J Range Manage 1989;42:217–22.
Royer F, Dickinson R. Weeds of Canada and the Northern United States. Edmonton: Lone Pine Publishing and The University of Alberta Press; 2006.
Sas-Nowosielska A, Kucharski R, Małkowski E, Pogrzeba M, Kuperberg JM, Kryński K. Phytoextraction crop disposal—an unsolved problem. Environ Pollut 2004;128:373–9.
Seymour M. Growing common vetch. In: White P, Harries M, Seymour M, Burgess P, editors. Producing Pulses in the Northern Agriculture Region. Bulletin 4656. Western Australia. Department of Agriculture; 2005. p. 63–9. Available online: http://www.agric.wa.gov.au/objtwr/imported_assets/content/fcp/lp/bulletin4656_PI.pdf.
Sharma RK, Agrawal M, Marshall F. Heavy metal contamination of soil and vegetables in suburban areas of Varanasi, India. Ecotoxicol Environ Safety 2007;66:258–66.
Singh OV, Jain RK. Phytoremediation of toxic aromatic pollutants from soil. Appl Microbiol Biotl 2003;63:128–35.
Sulev K. 2009. Personal communication.
Thomas SC, Bazzaz FA. Elevated CO_2 and leaf shape: are dandelions getting toothier? Am J Bot 1996;83:106–11.
United States Department of Agriculture (USDA), National Resources Conservation Service (NRCS). Plant Fact Sheet—New England Aster. Elsberry. MO: Elsberry Plant Materials Center; 2003. Available online: http://plants.usda.gov/factsheet/pdf/fs_syno2.pdf.
Weber JB, Mrozek Jr E. Polychlorinated biphenyls: phytotoxicity, absorption and translocation by plants, and inactivation by activated carbon. Bull Environm Contam Toxicol 1979;23:412–7.
White JC, Parrish ZD, Iseleyen M, Gent MPN, Iannucci-Berger W, Eitzer BD, Kelsey JW, Mattina MI. Influence of citric acid amendments on the availability of weathered PCBs to plant and earthworm species. Int J Phytoremed 2006;8:63–79.
Whitfield Åslund M, Rutter A, Reimer KJ, Zeeb B. The effects of specific repeated planting, planting density, and specific transfer pathways on PCB uptake by *Cucurbita pepo* in field conditions. Sci Total Environ 2008;405:14–25.
Whitfield Åslund M, Zeeb B, Rutter A, Reimer KJ. *In situ* phytoextraction of polychlorinated biphenyl- (PCB) contaminated soil. Sci Total Environ 2007;374:1-12.
Zeeb BA, Amphlett JS, Rutter A, Reimer KJ. Potential for phytoremediation of polychlorinated biphenyl- (PCB-) contaminated soil. Int J Phytoremediat 2006;8:199–221.
Zhang CB, Wang J, Qian BY, Li WH. Effects of the invader *Solidago canadensis* on soil properties. Applied Soil Ecology 2009;43(2–3):163–9.
Zimdahl RL. Weed–crop competition: a review. 2nd ed. Ames, IA: Wiley-Blackwell; 2004.
Zollinger RK, Ries JL, Hammond JJ. Survey of weeds in North Dakota-2000. North Dakota State University Agricultural Experiment Station Research Report ER-83; 2003. 97p.