Published in final edited form as:

Ecol Eng. 2013 August ; 57: 285–292. doi:10.1016/j.ecoleng.2013.04.052.

Rhizosphere Redox Cycling and Implications for Rhizosphere Biotransformation of Selected Polychlorinated Biphenyl (PCB) Congeners

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Abstract

Theoretically, sequential cycles of dechlorination followed by aerobic bio-oxidation are desirable to achieve complete degradation of a mixture of higher and lower chlorinated PCBs. In this research, soil was artificially contaminated with polychlorinated biphenyls (PCBs) in mixture and as single congeners, aged, and planted with two different plant species. Alternating redox cycles were created in the root zone of plants by flooding and draining the soil. Over 32 weeks, switchgrass (*Panicum virgatum*) and poplar (*Populus deltoids x nigra* DN34) planted systems that were exposed to alternate cycles of flooding performed better in reducing parent PCBs than planted systems that were not cycled ($p < 0.05$). The cycled systems also had a higher mass of PCB transformation products than the uncycled systems. Multiple cycles were necessary to achieve significant differences between the cycled and uncycled treatments.

Keywords

Redox; Moisture Content Cycling; Switchgrass; Poplar; Rhizosphere; PCB

1.0 Introduction

The persistence of polychlorinated biphenyls (PCBs) in the environment is driven by their relative inertness and this is exacerbated by the fact that there is no single redox environment that is conducive to their complete degradation. Higher chlorinated PCBs, i.e. those with 4 or more chlorine substituents are highly oxidized and as such are more amenable to degradation under highly reducing conditions. On the other hand, the more reduced congeners (with less than 4 chlorine substituents) are more readily transformed under highly oxidized conditions. At PCB contaminated sites it is highly unlikely that both of these conditions coexist, so one process will always predominate leaving behind the less

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favored PCB fraction. Therefore, in order to have complete PCB degradation both redox environments will have to be present. Having recognized this, a few researchers have undertaken studies designed to exploit the utilization of sequential cycles of anaerobic and aerobic conditions to enhance PCB degradation, with the intent of adapting this to engineered systems (Master et al. 2002, Fathepure and Vogel, 1991, Evans et al., 1996, Anid et al., 1993). For example, Anid and colleagues attempted to induce aerobic conditions into anaerobic sediments from the Hudson River which showed evidence of natural in situ reductive dechlorination occurring. They further subjected the sediments to anaerobic conditions for 76 weeks after which they added hydrogen peroxide (H_2O_2) and allowed the system to incubate for 96 days. There was a positive correlation between an increase in H_2O_2 concentration in the previously anaerobic sediments and reduction of total PCB concentration. They also indicated that there was a shift in the PCB congener profile to lower chlorinated congeners after anaerobic treatment and subsequent aerobic treatment.

These studies have either utilized bioaugmentation or added chemicals that may be inimical to the wellbeing of microbes. For example, H_2O_2 can be toxic to subsurface microorganisms at concentrations as low as 0.003%. Bioaugmentation has not had a lot of success in the field because sometimes the added organisms are outcompeted by natural biota.

It is widely held that plants can play an indirect role in the degradation of PCBs by providing the right environment in the root zone of the plant (rhizosphere) (Dzantor 2007; Mackova et al. 2007; Dzantor et al. 2000). Leigh et al. (2002) posited that flavonoidal compounds produced by plant roots could stimulate the growth of PCB degrading bacteria. They subjected *Burkholderia sp.* LB400, to three mulberry root flavones (morusin, morusinal and kuwanon C), which were the sole carbon source. They observed the same growth rate as when biphenyl was the carbon source, whereas there was no growth in the substrate free control. They also observed a 2 fold increase in phenolic compounds in the fine roots during the latter parts of the growing season, when most roots were dying. Thus they concluded that the dead fine roots of mulberry can provide a source of substrate for PCB degrading bacteria. This may have significant implications for rhizoremediation, because if this is the case for a number of plants, it means that if root growth can be stimulated during the growing season, then PCB degradation may be able to take place even as the roots die.

More importantly though, if redox conditions in the rhizosphere can be manipulated the potential exists for the development of an enhanced plant- microbe PCB biotransformation system. Inducing low redox conditions in the rhizosphere could allow bacteria to transform the higher chlorinated PCBs anaerobically, resulting in the accumulation of lower chlorinated PCBs. Higher redox conditions, could then result in further microbial transformation of the lower chlorinated PCBs, or uptake and transformation by plants since they are more soluble than their higher chlorinated counterparts. In such a system, the roots would provide additional electron donors for microbes to convert the PCBs to a form that is more readily available to plants thereby enhancing PCB degradation. However, what is not known is the extent of the effect that plants will have on the redox conditions in the rhizosphere, which could negatively impact the anaerobic degradation of the higher chlorinated PCBs by bacteria.

Given that these recent studies have indicated that planted systems are able to stimulate PCB degradation, the objective of the current study was to harness the ability of plants to enhance PCB degradation and couple that to the manipulation of redox conditions to further enhance PCB transformation since all previous studies examining the redox manipulation phenomenon have been bacteria based. Redox conditions were manipulated by creating alternate cycles of flooding and no flooding in one set of reactors (hereafter referred to as moisture content cycling). In addition, all previous redox manipulation experiments utilized multi-compartment systems or had single cycles, therefore, we also wanted to investigate the impact of multiple cycles in a single reactor.

2.0 Materials and Methods

2.1 Experimental Set up

Soil from Amana colonies IA, was passed through a 60 mesh sieve and artificially contaminated with tetra chlorinated PCB 52, PCB77 and hexa chlorinated PCB 153 separately and as a mixture of the three congeners. The soil was homogenized using the quartering technique. Quartering consists of dividing the soil into four quadrants on a quartering canvas and making several diagonal trajectories to mix the soil components together. Twenty passes (diagonal trajectories) were made to homogenize the soil thoroughly. To account for heterogeneity, 20 subsets of soil were collected from different locations, homogenized and analyzed in triplicate. Triplicate concentration measurements were conducted to establish the initial concentration, and it was compared to the target concentration for the purpose of quality assurance. The contaminated soil was aged for two months to reduce bioavailability and to ensure conditions more representative of field sites (Alexander et al., 2000, Thompson et al., 1998, White et al., 2006). The aged, contaminated soils were planted separately with switchgrass (*Panicum virgatum*) seeds from Adams-Briscoe Seed Co. (Jackson, GA) and with 22.9 cm poplar (*Populus deltoids x nigra* DN34) cuttings from Segal Ranch Hybrid Poplars Nursery (Grand View, WA).

Treatments consisting of switchgrass and poplar planted in uncontaminated soil were used as blanks and functioned as volatilization controls. Plants were grown under a 16 hour light/8 hour dark photo period with a light intensity of $200 \mu\text{mol m}^{-2}\text{s}^{-1}$ and at a temperature of 25 °C. Plastic rubber maid shoes boxes (33.8 cm × 21.6 cm × 11.9 cm (L×W×D)) with 1.9 cm holes drilled in the covers, lined with aluminum foil and containing 2500 g of soil were used as reactors. Holes (1.9 cm) were bored in covers of the reactors to facilitate measurement of redox potential and dissolved oxygen concentration during periods of flooding (low redox conditions). The plants were allowed to establish themselves for four (4) weeks. After 4 weeks, one set of plants were subjected to alternate cycles of seven (7) days flooding (to induce anaerobic conditions) and seven (7) days of no flooding (aerobic conditions). Another set had a normal watering regimen, with no flooding. To achieve flooding, three liters of deionized water was initially added to the reactors and supplemented as dictated by transpiration rates. Transpiration typically functioned as an efficient mechanism for water withdrawal, so there was no need to withdraw excess water at the end of the flooding cycle. The soil was sampled and analyzed 8 weeks after planting, and at

regular intervals ranging from two to eight weeks thereafter, up to a period of thirty two (32) weeks.

Twelve (12), five (5) g samples of soil were collected randomly from each treatment using a Lock and Hold™ syringe (Ben Meadows Company WI, USA) and homogenized prior to analysis. At the end of exposure (32 weeks), soil and plant materials were sampled and analyzed for PCB content using GC/MS/MS triple quadrupole mass spectrometry (Agilent Technologies 6890N GC with an Agilent 7683 series autosampler coupled to a Waters Micromass Quattro micro GC mass spectrometer (Milford, MA)). PCBs 14, d65, and 166 were used as surrogate standards and PCB 204 was the internal standard. The experimental set up and analyses were carried out in triplicate. A schematic representation of the reactors used, the procedure for sampling and adding water and the procedure for making redox measurements can be seen in Figure 1.

2.2 PCB Extraction

Denaturation and extraction of PCB in soil and plant material was conducted by adding three (3) milliliters per gram of a 1:1 hexane/acetone mixture to 5 grams of grounded homogenized soil and sonicating for 1 hour. Prior to sonification, the samples were spiked with 50 ng of PCB14 (3,5-dichlorobiphenyl), deuterated PCB65 (2,3,5,6-tetrachlorobiphenyl) and PCB166 (2,3,4,4',5,6-hexachlorobiphenyl) (Cambridge Isotope Laboratories, Inc.), which were used as surrogate standards. Surrogate recoveries ranged from 87.2±3.1% to 96.4±3.8% for PCB 14, 92.8±4.7% to 105.1±4.2% for PCB 65 and 93.2±2.5% to 106.4±2.5% for PCB 166.

The sonicated material was centrifuged at 3000 rpm for 5 minutes, after which the supernatant was transferred to a fresh vial. A second extraction was performed and the supernatants combined. The combined supernatant was evaporated to dryness using rotary evaporation and the solvent changed to hexane. Any loss by rotary evaporation was accounted for using the surrogate standard recoveries. Removal of lipids and other polar substances was achieved by double extraction with concentrated sulfuric acid and hexane. This hexane extract was concentrated to approximately 0.5 ml under a gentle stream of N₂. The concentrate was eluted with 10 ml of hexane through a filter consisting of 0.1g of silica (70–230 mesh, Fisher Scientific, Inc.), 0.1g of anhydrous sodium sulfate (Na₂SO₄) and 0.9 g silica gel acidified with H₂SO₄ (2:1). The eluent was concentrated and PCB204 (2,2',3,4,4',5,6,6' octachlorobiphenyl) was added as an internal standard before analysis by GC/MS/MS triple quadrupole mass spectrometry (Agilent Technologies 6890N GC with an Agilent 7683 series autosampler coupled to a Waters Micromass Quattro micro GC mass spectrometer (Milford, MA)). The gas chromatogram (GC) was fitted with a Supelco SBP-Octyl capillary column (30 m × 0.25 mm ID, 0.25 µm film thickness) with helium as carrier gas at a constant flow rate of 0.8 ml min⁻¹. The GC operating conditions were as follows: injector temperature 270 °C, interface temperature 290 °C, initial temperature 75 °C, initial time 2 min. The GC temperature program was 75 to 150 °C at 15 °C min⁻¹, 150 to 290 °C at 2.5 °C min⁻¹, and final time 1 min. Hu et al. (2010) describes the procedure for identification and quantification of the PCBs.

2.3 Measurement of Redox Conditions

Redox measurements were obtained using a Hanna Instruments Redox/pH combination meter. For quality assurance purposes, the accuracy of the ORP meter was checked with 475 mv and 229 mv redox buffers (Aqua Solutions).

2.4 Statistical Analysis

Microsoft Excel Analysis Toolpak's ANOVA analysis and Students' t-test were used for statistical testing. The significance level of 0.05 was utilized to indicate whether the treatments were significantly different than the controls.

3.0 Results and Discussion

3.1 Redox Measurement

The soil redox potential in the moisture content cycled treatments for the mixture and single congener exposure during a one week flooding cycle is illustrated in Figure 2. During periods of flooding, the planted systems showed evidence of hypoxia, but oxygen was not sufficiently depleted to produce anaerobic conditions. The inability to develop bulk anaerobic or anoxic conditions in the planted system was probably due to plant transfer of oxygen to the rhizosphere during photosynthesis. In the planted systems the redox potential became poised at about 20 millivolts (mV). The unplanted systems had lower redox potential than the planted systems and were anoxic (0-200 mV).

Figure 3 depicts a longer trend for the redox potential for the cycled treatment that contained the PCB mixture and shows that even though anaerobic conditions didn't develop throughout the soil column in the flooded reactors, there were variations in redox potential which mirrored the manipulation of the soil moisture content.

3.2 Measured versus Target Initial PCB Concentration

The targeted initial concentration for each congener in the mixture (PCB 52, PCB 77 and PCB 153) was 500 ng g⁻¹. In the single congener exposures, an initial concentration of 1000 ng g⁻¹ was targeted. However, the measured initial concentrations were different from the target in both the mixture and single congener treatments, probably due to the heterogeneity of the soil matrix. In the mixture, the measured initial concentrations were 573 ± 29 ng g⁻¹, 512 ± 24 ng g⁻¹ and 499 ± 25 ng g⁻¹ respectively for PCB 52, PCB 77 and PCB 153. For the single congener exposure, the measured initial concentrations were 1120 ± 58 ng g⁻¹ (PCB 52), 1012 ± 3 ng g⁻¹ (PCB 77) and 1033 ± 28 ng g⁻¹ (PCB 153).

3.3 PCB Dissipation in Mixture: Switchgrass Planted Soil

Figure 4 compares the concentration of PCB 52, PCB 77 and PCB 153 in soil containing a mixture of the three congeners and planted with switchgrass after 32 weeks of incubation. A 53% decrease in soil PCB 52 concentration was obtained when the soil containing the mixture was planted with switchgrass, and did not undergo cycling of the water moisture content. On the other hand, there was a 56% reduction in the soil PCB 52 concentration for the cycled treatment. In both cases, this represented a significant decline when compared to

the initial concentration ($p<0.05$). However there was no significant difference in reduction of PCB 52 concentration between the cycled and uncycled treatments ($p<0.05$).

With respect to PCB 77 dissipation, the switchgrass planted uncycled treatment containing the mixture recorded a 44% decline, while the cycled treatment registered a 48% diminution (Figure 4). Both the cycled and uncycled treatments had significant reductions when compared to the initial PCB 77 concentration in the mixture ($p<0.05$). However, the cycled treatment had significantly higher decrease in soil PCB 77 concentration than the uncycled system ($p<0.05$).

Compared to the initial concentration in the mixture, the concentration of PCB 153 in soil planted with switchgrass diminished by 49% in the treatment that did not undergo moisture content cycling. The cycled treatment recorded a 55% decrease. This represented a significant difference in dissipation between the cycled and uncycled treatments ($p<0.05$). Compared to the initial PCB 153 concentration, both the cycled and uncycled systems had significant declines ($p<0.05$).

3.4 PCB Dissipation in Single Congener Exposure: Switchgrass Planted Soil

The PCB reduction results for the single congener exposure with switchgrass as the plant species are shown in Figure 5. After 32 weeks of exposure, there was a 56% reduction in the soil PCB 52 concentration for the uncycled treatment, and 63% for the cycled system. This represented a significant decrease when compared to the initial concentration ($p<0.05$). Overall, both the uncycled and cycled treatments had significant declines in soil PCB 52 concentration ($p<0.05$), but the cycled treatment had a significantly higher reduction than the uncycled treatment.

When PCB 77 was used as the sole contaminant and the soil was planted with switchgrass, the cycled treatment showed a 54% decline (Figure 5). This diminution was significantly higher than the 48% decrease observed with the uncycled treatment ($p<0.05$), (Figure 5). With respect to the initial PCB concentration in the soil, both the uncycled and cycled treatments had significantly diminished PCB 77 concentrations at the end of exposure ($p<0.05$).

There was a 44% reduction in soil PCB 153 concentration for the planted cycled treatment while a 51% decline was recorded with the planted uncycled treatment (Figure 5). In the single congener exposure experiment with PCB 153 and switchgrass, both the cycled and uncycled treatments had significantly reduced concentration in the soil after 32 weeks ($p<0.05$). However, the cycled treatment exhibited a significantly higher diminution than the uncycled treatment ($p<0.05$).

3.5 PCB Dissipation in Mixture: Poplar Planted Soil

The PCB 52 concentration in soil planted contaminated with the mixture of PCB 52, PCB 77 and PCB 153 and planted with poplar after 32 weeks of incubation is shown in Figure 6. Both the moisture content cycled and uncycled treatments recorded significant declines in the PCB 52 concentration in the soil ($p<0.05$). A 57% decrease in PCB 52 concentration was obtained when the soil moisture content was cycled. A statistically analogous reduction of

54 % was registered in the uncycled treatment ($p < 0.05$). Percentagewise, the results obtained with PCB 52 diminution and poplar as the plant species, were statistically similar to those obtained for PCB 52 decrease in the mixture when switchgrass was the plant species (Figure 4).

There was a 52% reduction in soil PCB 77 concentration in the mixture for the moisture content cycled treatment that was planted with poplar. In contrast, a significantly lower decrease of 42% was recorded for the uncycled treatment ($p < 0.05$). Compared to the initial PCB 77 concentration in the mixture, both the cycled and uncycled treatments recorded statistically significant declines ($p < 0.05$). With regards to PCB77 dissipation in the mixture and plant species, the results obtained with the poplar planted soil were statistically similar to those achieved with switchgrass planted soil ($p < 0.05$).

Using poplar as the plant species, the PCB 153 concentration in the planted soil contaminated with the mixture diminished by 48% in the uncycled treatment, and by 55% in the cycled treatment (Figure 6). The diminution recorded with the cycled treatment was significantly higher than that achieved with the uncycled treatment ($p < 0.05$). At the end of the exposure period, both the cycled and uncycled treatments had significantly reduced concentrations of PCB 153 when compared to the initial PCB 153 concentration in the mixture. Like the other congeners in the mixture, the PCB 153 reduction achieved in poplar planted soil was statistically equivalent to that seen in switchgrass planted soil ($p < 0.05$).

3.6 PCB Dissipation in Single Congener Exposure: Poplar Planted Soil

The reduction of soil PCB 52 concentration in the single congener exposure with poplar as the planted species is shown in Figure 7. A 57% decrease was obtained for the treatment that underwent cyclic manipulation of soil moisture content whereas a 49% decline was observed with the uncycled treatment. Significant reductions in soil PCB 52 concentration were obtained in both the cycled and uncycled treatments when compared to the initial concentration ($p < 0.05$). However, the cycled treatment had a significantly greater loss than the uncycled treatment ($p < 0.05$). The decreases in PCB 52 concentration observed with poplar planted soil were significantly lower than the declines seen with switchgrass in a similar single congener exposure experiment ($p < 0.05$).

Figure 7 shows the reduction of soil PCB 77 concentration with poplar as the planted species and PCB 77 as the sole contaminant. The soil PCB concentration in the moisture content cycled treatment diminished by 47% reduction at the end of exposure. On the other hand, a significantly lower decrease of 39% was recorded for the uncycled treatment. Both the cycled and uncycled treatments had significant reductions in their PCB 77 concentration when compared to the initial concentration. Again, lower reductions were experienced with PCB 77 as the single congener and poplar as the plant species, when compared with the switchgrass system and PCB 77 as the single congener.

When PCB 153 was the sole contaminant and poplar was the plant species, a reduction of 49% was registered with the moisture content cycled treatment. In comparison, the decline recorded in the uncycled treatment was 41%. The decrease observed in the moisture content cycled treatment was significantly higher than the diminution in the uncycled treatment

($p < 0.05$). Compared to the initial PCB 153 concentration, both the cycled and uncycled treatments had significant reductions in their soil PCB concentration at the end of incubation ($p < 0.05$). Similar decreases in PCB 153 concentration were obtained with the poplar and switchgrass planted systems. ($p < 0.05$).

The decrease in parent compound concentration in the uncycled and cycled planted systems at most time points were similar for both the single congener exposures and the exposures containing the mixture ($p < 0.05$) (supplemental information Figures S3-S8). However at the end of exposure there were significant differences between the the cycled and uncycled treatments in all cases except one. This could be attributed to the fact that for the cycled systems, neither anaerobic nor sulfidogenic conditions developed at any time during the 7 days flooding period that was intended to create anaerobic conditions in the root zone. This necessitated the need for multiple cycles of redox manipulation to produce any significant difference between the cycled and uncycled treatment.

While methanogenic conditions are desirable for anaerobic microbial reductive dechlorination to occur, it is possible to effect reductive dechlorination in a sulfidogenic environment (Fava et al., 2003, Kuo et al. 1999). Both sulfate reducing and methanogenic bacteria have been hypothesized as mediating the reduction of single congeners similar to the one used in this study, and highly chlorinated congeners in Aroclor mixtures (Kuo et al., 1999, Fava et al., 2003, Zandaroli et al., 2006). These reductions resulted in the accumulation of less toxic lower chlorinated congeners.

The inability to develop anaerobic conditions in the root zone means that it is not tenable to achieve these conditions at the the 7 days time scale. The inability to induce anaerobic conditions in the root zone may have resulted from plant produced oxygen during photosynthesis. Plants can affect soil oxygen levels through radial oxygen transfer from the roots as evidenced by the diurnal fluctuation shown when *Carix nigra* was planted in sand (Adema et al. 2003). Similarly, Nzungung et al. (2004) working in hydroponic solution was able to see significant diurnal swings in redox potential in willow planted treatments. The diurnal fluctuations were of the order of 450 mV.

There have been reports of attempting to use combination of anaerobic and aerobic systems to enhance microbial degradation of PCB mixtures containing higher and lower chlorinated congeners. However these have always been two compartment systems whereby the contaminant is held for a long period of time in anaerobic conditions and then the effluent is moved to an aerobic environment (Fathepure and Vogel, 1991, Master et al., 2002). The novelty of this system is the use a single reactor to accomplish the same purpose. The natural fluctuations in redox potential, if large enough and often enough, could act as a microzone for the bigger setup. Plant influenced root zone aeration is suggested by the fact there was a quicker drop in the redox potential in the unplanted cycled system than with the planted cycled system (Figure 2). Differences in the cycled and uncycled treatments were not readily apparent and multiple cycles were needed for the impact of cycling to be significant in a planted system (supplemental information Figures S3-S8), possibly due to the short cycling periods which are necessary to maintain plant health.

In addition to dissipation of parent compounds, several transformation products of the parent PCBs were observed in the cycled and uncycled treatments. For PCB 153 the transformation products measured ranged from pentachlorinated to dichlorinated compounds. PCBs 52 and 77 produced dechlorinated compounds ranging from trichlorinated to monochlorinated congeners. A mass balance on the switchgrass and poplar planted systems indicated that there was a higher mass of transformation products in the cycled system in comparison to the uncycled system (Tables 1 and 2).

4.0 Conclusions

There was difficulty in lowering the redox potential to sulfidogenic conditions in the planted reactors as designed here. This suggests plant oxygen transfer downwards to the roots and soils. The soil reactors with plants became redox “poised” at about +20 mV, while the unplanted reactors became poised at about –150 mV. It is possible, that with a longer period of flooding sulfidogenic conditions can be achieved in planted reactors. However, even under marginally positive bulk redox conditions, the cycled switchgrass and poplar planted systems showed significantly higher dissipation of parent PCB compounds. In addition, the cycled planted systems had a higher mass of transformation products than uncycled planted systems. Multiple cycles were necessary to achieve significant differences between the cycled and uncycled treatments because of the short cycles needed to maintain plant health. For a short multiple cycle regime to be effective, it will have to be combined with planting because the impact of cycling on PCB dissipation and transformation in the switchgrass and poplar planted systems was not replicated in the unplanted system (supplemental information Figures S1 and S2). Planted systems clearly showed greater PCB transformation than unplanted systems, and those where redox was cycled, showed significantly greater transformations than uncycled treatments.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

The authors would like to acknowledge the National Institute of Environmental Health Sciences (NIEHS) Superfund Research Program (SRP) Grant No. P42ES13661, for providing funding for this research. Likewise, this work would not be possible without the expert analytical support provided by Dr. Dingfei Hu. We also wish acknowledge the contribution of Dr. Hans Lehmler for providing PCB congeners.

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Figure 1. Schematic of reactors, procedure for sampling and procedure for measuring D.O and ORP. The poplar system representation is on top and the switchgrass system representation is on the bottom.

Figure 2.

Representative redox potential in flooded soil containing a mixture of PCB 52, 77 and 153 and single congeners and planted with switchgrass or poplar. Also shown is the redox potential in the flooded unplanted system.

Figure 3. Redox potential in flooded soil containing a mixture of PCB 52, 77 and 153 and planted with switchgrass or poplar. Also shown is the redox potential in the flooded unplanted system.

Figure 4.

Decrease of parent PCB in soil contaminated with mixture of PCB 52, PCB 77 and PCB 153 and planted with switchgrass. SG = switchgrass. The spike congeners were undetectable in the controls which were not spiked. *= significant reduction when compared to initial concentration ($p < 0.05$). Φ = significantly higher reduction when compared to uncycled treatment ($p < 0.05$). Error bars are 1 standard deviation.

Figure 5.

Decrease of parent PCB in soil contaminated PCB 52, PCB 77 and PCB 153 as the sole contaminants and planted with switchgrass. SG = switchgrass. The spiked congeners were undetectable in the controls which were not spiked. *= significant reduction when compared to initial concentration (p<0.05). Φ = significantly higher reduction when compared to uncycled treatment (p<0.05). Error bars are 1 standard deviation.

Figure 6.

Decrease of parent PCB in soil contaminated with mixture of PCB 52, PCB 77 and PCB 153 and planted with poplar. POP = Poplar. The spike congeners were undetectable in the controls which were not spiked. *= significant reduction when compared to initial concentration ($p < 0.05$). Φ = significantly higher reduction when compared to uncycled treatment ($p < 0.05$). Error bars are 1 standard deviation.

Figure 7.

Decrease of parent PCB in soil contaminated with PCB 52, PCB 77 and PCB 153 as the sole contaminants and planted with poplar. POP = poplar. The spiked congeners were undetectable in the controls which were not spiked. * = significant reduction when compared to initial concentration ($p < 0.05$). Φ = significantly higher reduction when compared to uncycled treatment ($p < 0.05$). Error bars are 1 standard deviation.

Table 1
Molar Mass Balance in Switchgrass Planted System with and without Moisture Content Cycling

	Parent Compound In Soil (mole %)	Transformation Products in Soil (mole %)	Roots (mole %)	Shoots (mole %)	Recovered (mole%)
PCB52 Uncycled	43.6	55.1	2.6	<0.1	101.3
PCB52 Cycled	37.2	63.0	3.5	<0.1	103.7
PCB77 Uncycled	52.0	42.1	4.4	<0.1	98.5
PCB77 Cycled	46.5	55.5	4.5	<0.1	106.5
PCB153 Uncycled	56.1	40.1	2.2	<0.1	98.4
PCB153 Cycled	49.3	46.9	2.2	<0.1	98.4

Table 2
Molar Mass Balance in Poplar Planted System with and without Moisture Content Cycling

	Parent Compound In Soil (mole %)	Transformation Products in Soil (mole %)	Roots (mole %)	Leaf (mole %)	Recovered (mole %)
PCB52 Uncycled	51.2	45.9	3.5	<0.1	100.6
PCB52 Cycled	46.4	56.2	3.4	<0.1	106.0
PCB77 Uncycled	61.1	35.7	2.5	<0.1	99.3
PCB77 Cycled	53.8	47.4	2.6	<0.1	103.8
PCB153 Uncycled	59.2	35.3	3.5	<0.1	98.0
PCB153 Cycled	51.0	47.7	4.3	<0.1	103.0