Available online at www.sciencedirect.com
ScienceDirect
Chemosphere 68 (2007) 191–198
CHEMOSPHERE
www.elsevier.com/locate/chemosphere

Polychlorinated biphenyls in tree bark near a former manufacturing plant in Anniston, Alabama

Mark H. Hermanson [a,*], Glenn W. Johnson [b]

[a] University of Pennsylvania, Department of Chemistry, 231 S. 34th Street, Philadelphia, PA 19104-6323, United States
[b] University of Utah, Energy and Geoscience Institute, 423 Wakara Way Suite 300, Salt Lake City, UT 84108, United States

Received 6 July 2006; received in revised form 8 November 2006; accepted 13 November 2006
Available online 20 February 2007

Abstract

Tree bark samples were collected to identify the relative amounts and congener profiles of atmospheric polychlorinated biphenyls dissolved into bark lipids from the gas phase in Anniston, Alabama, USA, where PCBs were manufactured from the 1920s until 1971. The area is heavily contaminated with PCBs: At least 4550 metric tons (mt) of PCB and 14000 mt of PCB distillation residue, known as Montar, remain buried in two landfills near the plant site. A minimum of 20.5 mt of PCBs were emitted to the atmosphere by the plant between 1953 and 1971 based on emissions figures for 1970. Bark results show that total PCB concentrations range over more than three orders of magnitude from 171927 ng/g lipid near the plant/landfill area, dropping exponentially to 35 ng/g lipid at a distance of about 7 km. The exponential trend is highly correlated ($r = -0.77$) and significant ($\rho < 0.05$). The most concentrated tree started growing after 1971 showing that atmospheric PCB concentrations remained high after PCB production ended. All PCB congener profiles show persistent congeners 31 + 28, 52, 66, 153, 138, and 180. Congener profiles from trees growing near the plant/landfill all have somewhat similar profiles but those growing during PCB production show high molecular mass compounds not usually found in the atmosphere and not found in younger trees, even in the most concentrated sample. We believe that high-temperature Montar disposal released high molecular mass PCBs into the gas phase which were dissolved into older tree bark lipids.

Keywords: PCB; Congeners; Lipid; Montar; Partition coefficient; Octanol/air

1. Introduction

Over a period of about 45 years from the 1920s until 1971, a minimum of 400000 mt of polychlorinated biphenyls were manufactured in Anniston, Alabama, USA (Hermanson et al., 2003). During production, a minimum of 4550 mt of PCB were discarded into two landfills to the south and west of the plant (USEPA, 1979). During the last 18 years of that period, a minimum of 20.5 mt of PCBs were emitted from the plant into the atmosphere based on estimated loses in 1970 and production figures from that time (Wright, 1970a). Pre-1970 atmospheric losses were known to be higher, however, and it has been estimated that during peak production in 1968–69, 7.5 mt of PCB were emitted in one 12-month period (Ramsey, 1970; Wright, 1970a). These estimates do not include any effect of off-gassing from landfills. During production, a waste product called Montar was removed regularly from the bottoms of distillation towers at 380 °C. Montar was composed of chlorine in about the same fraction of PCB product (~42% for Aroclor 1242) and other residues. Fumes from this material were considered to be "toxic, extremely irritating to mucuous membranes, eyes and respiratory tract" (Williams et al., 1966) and harmful to employees (Edelblut, 1957). Montars were cooled over a period of 6–10 h during which gases were vented. Since the draining temperature exceeds the boiling point of all PCB congeners, any PCB residue in Montar would have been

* Corresponding author. Tel.: +1 215 573 8727; fax: +1 215 573 2112.
E-mail address: markhh@sas.upenn.edu (M.H. Hermanson).

0045-6535/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.chemosphere.2006.11.068

transferred to the gas phase as the material was moved from the plant to the landfill. Wright (1970b) reported 8630 ng/m^3 gas phase $\sum^{PCB}$ at a Montar vent at the plant during a period of low PCB production in 1970. A total of 14000 mt of Montar were discarded into the landfills in Anniston (USEPA, 1979).

There was no air sampling in Anniston before 1997, so PCB air concentrations during times of Aroclor production can only be estimated from emissions data. In 1970, atmospheric PCB emissions were 1.3 kg/day after efforts to reduce them (Wright, 1970b). Using this rate in a box model (Peck and Hornbuckle, 2005) covering the area of Anniston (28.5 km^2) to 2 m depth, air in the box would have had a $\sum^{PCB}$ concentration of 20680 ng/m^3. During peak production in 1968–69, that amount would have been 359000 ng/m^3. Diffusion to the atmospheric mixing height would have diluted these amounts, but the effects of these daily emissions surely impacted the environment and residents of Anniston, particularly near the plant.

Between May 1997 and June 1998, air samples were collected at two sites in Anniston, one about 600 m east of the plant site and 500 m north from the south landfill, known as Mars Hill, and the other about 1.25 km NW from the plant, known as Carter. Total gas-phase PCB concentrations were as high as 82 ng/m^3 and averaged 27 ng/m^3 at Mars Hill. At Carter, a residential area without known PCB landfills or industrial uses, the maximum concentration was 40 ng/m^3 (average 9.8 ng/m^3) (Hermanson et al., 2003). While these amounts are small compared to production-era estimates, they are very high relative to concentrations observed since the 1980's at other PCB-contaminated sites. The Mars Hill average is more than four times greater than the maximum average (6.6 ng/m^3) observed near the Akwesasne Reserve at Massena, NY in 1993, an area heavily impacted by PCB (Chiarenzelli et al., 2000). It is nine times greater than the highest annual average observed in Chicago in the early 1990s (~3.1 ng/m^3) which is similar to the maximum annual average in Bloomington, IN in 1986–88 (Hermanson and Hites, 1989; Buehler and Hites, 2002). The average concentrations at these latter two sites are about the same as the USEPA Region 3 risk based concentration for ambient air (3.1 ng/m^3) (http://www.epa.gov/reg3hwmd/risk/human/index.htm). These extremes in Anniston show the effects of large local PCB sources that have continued emitting to the atmosphere for decades after production ended.

With the absence of air-monitoring data during times of Aroclor production in Anniston, we need a proxy for historical PCB concentrations in air in addition to the estimates made above. Analysis of PCBs in tree bark is used here to identify the impact of the large PCB emissions in the 1960s and 1970s and to learn the effects of high existing air concentrations. Tree bark has been used as an indicator of atmospheric PCB and other contamination in areas with and without significant local sources (Meredith and Hites, 1987; Hermanson and Hites, 1990; Simonich and Hites, 1995; Schulz et al., 1999; Clarkson et al., 2002; Zhu and Hites, 2006). Tree bark contains some lipid which makes it a passive accumulator of compounds from the gas phase over the lifetime of the tree. Compounds with high octanol (lipid)/air partition coefficients (K_{oa}) will be favorably accumulated in bark. PCB log K_{oa} values range from about 6.65 (PCB 1) to 11.96 (PCB 209) (at 20 °C) depending generally on level of chlorine substitution on the molecule (Zhang et al., 1999). Since these values are high, an area like Anniston with probable historically high atmospheric PCB concentrations should show high tree bark concentrations in areas of local contamination.

PCBs also have octanol/water partition coefficients (log K_{ow}) ranging from 4.50 to 8.26 and are considered to be hydrophobic; they will not be translocated from contaminated soil by water in a tree's vascular system (Miller et al., 1984). However, PCBs and similar compounds that evaporate from contaminated soil can be found in tree bark. Bark is considered to be a dead tissue, so PCBs dissolved in bark lipids will not be metabolized (Schulz et al., 1999).

Our objective is to use tree bark to learn where the PCB contaminated areas are in Anniston, what the history has been based on comparative ages of trees, and what the PCB congener profiles tell us about different sources.

2. Methods

In 1998, bark was collected from 24 trees in and around Anniston (Fig. 1). Half of the samples were collected from sites near the plant, including the two air sampling sites. The other samples were collected to identify PCB exposure conditions at increasing distances and different directions from the plant. All of the sites were residential or wooded. In 2003, 11 samples were collected from a smaller area of residential sites to the north, northwest and northeast of the PCB plant, and six samples were collected near the south landfill which is known to contain PCB production waste and Montar (USEPA, 2001). Our emphasis here is on the 1998 samples which cover a broad area.

An area of tree trunk about 100 cm^2 at breast height was cleaned of non-bark residues (lichens, moss, etc.) and sanded if necessary. Bark was removed with a chisel previously rinsed with dichloromethane. Bark chips fell directly into a pre-cleaned jar with a lid lined with pre-cleaned aluminum foil (1998) or Teflon (2003). Samples were stored and shipped frozen.

In the lab, bark chunks were chiseled into pieces no larger than 1 cm^2. Between 25 and 45 g were spiked with surrogate standard (PCB 14 (200 ng), PCB 65 (60 ng) and PCB 166 (50 ng)) and soaked in 300 ml 1/1 (v/v) acetone/hexane in a Soxhlet extractor for 30 min before the extractor began running for a minimum of 16 h with three drainings and refillings per hour. The respective surrogate recovery values for all samples analyzed, averaging 74% (PCB 14), 85% (PCB 65), and 78% (PCB 166), are within the acceptable range of 50–125%. After extraction, sample volume was reduced to about 2 ml, loaded onto silica-gel

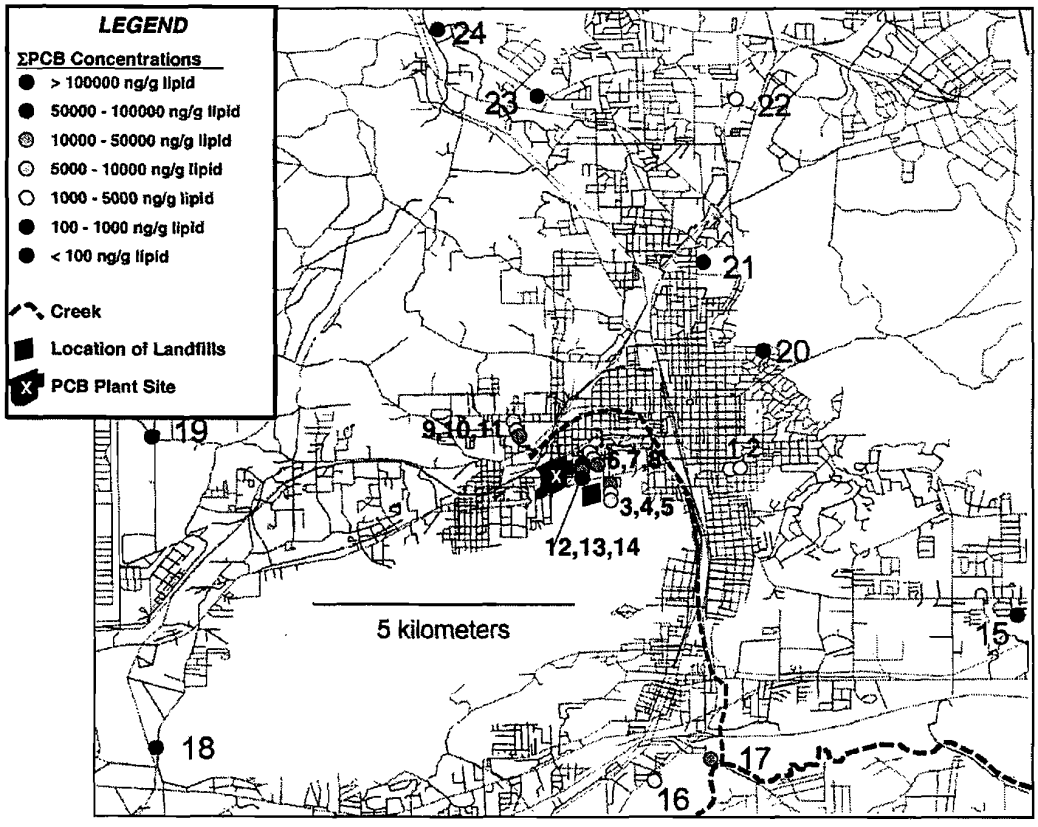

Fig. 1. General area and street map of Anniston, Alabama. The numbered sites are tree bark collection areas in 1998. Mars Hill (samples 12, 13, 14) and Carter (9, 10, 11) were air sampling sites in 1997–98. Samples collected in 2003 came from sites to the north, northwest and northeast of the plant site and from the south landfill.

(deactivated 3.5% with water) in a chromatography column (1.1 cm × 23 cm), and eluted with 60 ml hexane. The eluate volume was reduced to about 4 ml and internal standards added (80 ng PCB 30 and 60 ng PCB 204). A 2 μl aliquot of sample was injected into a gas chromatograph with electron capture detection (GC-ECD) equipped with a 5%-phenyl-methylpolysiloxane (DB-5) capillary column. The injector temperature was 250 °C and detector was 350 °C. The system was calibrated using a modification of the congener-specific PCB analysis method used for analysis of Anniston air samples (Hermanson et al., 2003). A total of 108 PCB congeners were analyzed and 96 of them are reported here as shown in Fig. 3. The elution order is that from the DB-5 column.

Lipid mass was measured using a 5 g subset of each sample which was sonicated in a beaker of 1/1 (v/v) acetone/hexane for 30 min. The solvent with the dissolved lipid was removed from the beaker, with solvent washings, and filtered. The filtrate was allowed to dry in a covered, preweighed aluminum pan. After drying, the remaining net mass was the lipid. The concentration of each congener was lipid normalized, and the sum of congeners is total PCB. Lipid content ranged from 0.24% to 7.3% of total bark mass for all trees sampled.

3. Results

3.1. Total PCB trends in tree bark in Anniston

Total PCB concentrations in all 41 tree bark samples from 1998 and 2003 ranged from a maximum value of 171927 ng/g lipid nearest the PCB plant at Mars Hill (#14) to 35 ng/g lipid at a distance of about 7 km away near the Anniston Army Depot (#19). The most distant tree, at Coldwater Treatment Plant (#18), 9 km from the PCB plant, had a concentration of 80 ng/g lipid (Fig. 1). The logarithmic scaled concentration vs. linear distance relationship is second order, highly correlated ($r = -0.77$) and significant ($\rho < 0.05$), and holds without consideration of tree age, species or direction from the plant site (Fig. 2). High concentration outliers that appear at 6–6.2 km from the plant were collected near the Anniston wastewater treatment plant (#17, WWTP), a site known to contain PCB contaminated materials from chemical spills from the PCB plant into the sewers (Coley and Stutz, 1966) and likely affected by PCB contamination from nearby Snow and Choccolocco Creeks (Tucker, 1970). Sludge is air-dried at this site which is likely to result in PCB evaporation to the atmosphere as observed in another

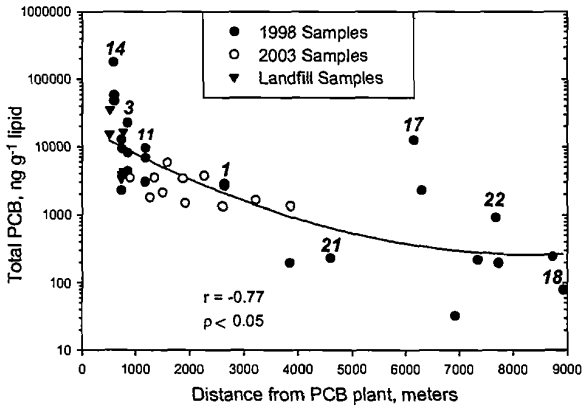

Fig. 2. Total PCB concentrations vs. distance from the PCB manufacturing plant for 1998 and 2003 samples. The trees with numbers in bold face are included in discussion of PCB congener profiles.

investigation where PCB contaminated sediments were air dried (Chiarenzelli et al., 1996).

These results show clearly that during the lifetimes of the trees, there have been very high atmospheric PCB concentrations near the PCB plant and landfills and at some other sites affected by these same sources.

The Mars Hill site has the three highest total PCB concentrations in bark (Fig. 2) and is the site where highest air concentrations were also observed (Hermanson et al., 2003). The most concentrated sample at Mars Hill (#14) was from a cherry tree estimated to be 25 years old in 1998. It started growing after PCB production ended in Anniston, showing that atmospheric PCB concentrations and exposures in the area where it grew remained high after Aroclor production ceased in 1971. The area near where tree #14 was growing was subject to flooding by south landfill runoff until 1996, apparently resulting in significant local soil contamination which is the likely source of PCB found in trees growing there.

3.2. PCB congener profiles

The percent-of-total PCB congener profile of the Mars Hill #14 sample is roughly in the Aroclor 1248 weight range, with a secondary contribution of heavier congeners more typical of Aroclors 1254 and 1260 (Fig. 3). Records show that eight Aroclors (all but 1016) were produced in Anniston, and that Aroclor 1242 was produced in greatest mass. This is consistent with sales records showing that Aroclor 1242 accounted for more than half of US sales in the period 1954–1974 (Durfee et al., 1976; Johnson et al., 2006). The low relative proportions of lighter congeners in Mars Hill bark samples – those more typical of Aroclor 1242 rather than Aroclor 1248 – does not preclude the contribution of an Aroclor 1242 related source. It has been shown in the laboratory (Chiarenzelli et al., 1997; Johnson et al., 2006) and in the field (Magar et al., 2005) that volatilization and partitioning of lighter congeners in Aroclor 1242 to air can yield a residual tissue congener pattern that more closely resembles Aroclor 1248. Considering the values of K_{oa} for the light congeners, their absence from tree bark in areas with high Aroclor 1242 use is not unusual and has been observed at other sites (Hermanson and Hites, 1990).

Tree bark samples collected from a site about 400 m SE from Mars Hill (Edwards #3 – Fig. 1) shows a very similar pattern to that at Mars Hill #14 (Fig. 3) with the exception that there are notably higher proportions of heavy octa and

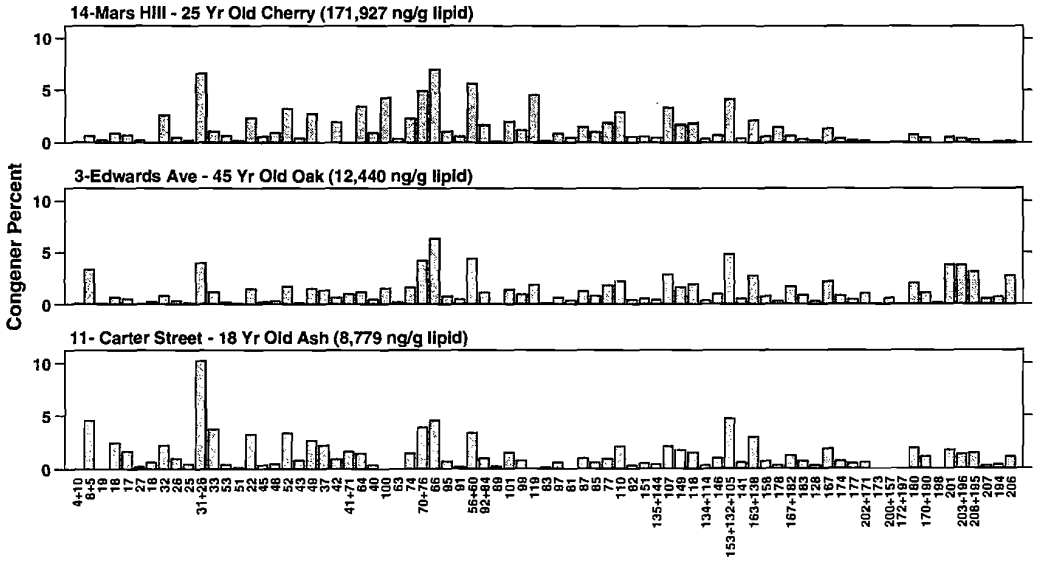

Fig. 3. Percent-of-total PCB congener profile comparisons for three tree bark sites near the plant/landfill area: Mars Hill (top, tree # 14), Edwards Avenue (middle, tree #3), and Carter (bottom, tree #11). Note tree type and age. The congener patterns are not similar ($\cos\theta < 0.80$ for comparisons of tree #14 with #3 and #11).

nona chlorinated congeners – in particular PCB 201, PCB 203+196, PCB 208+195, and PCB 206. These congeners are characteristic of heaviest Aroclors such as Aroclor 1268 (Rushneck et al., 2004). However, such heavy congeners would also be characteristic of the distillation residue (Montar) resulting from the production of many, if not all Aroclors. The Edwards site is east from the landfills and is influenced by the westerly and southwesterly winds which prevail about 30% of the time at the Anniston airport. The Edwards tree grew during the PCB production period when hot liquid Montar was discarded in the landfills. The Mars Hill site, while almost as close to the landfills as Edwards, began growing after PCB production in Anniston ended and was not exposed to any atmospheric Montar residues. The appearance of apparent Montar residues in the Edwards tree suggests that PCBs that are dissolved into tree bark lipids are retained for decades, likely as long as the tree retains the bark.

A third variant of this congener profile is observed at Carter (#11, Figs. 1 and 2). This congener pattern (Fig. 3) differs from the Mars Hill (#14) and Edwards (#3) patterns because it has a higher relative proportion of lighter congeners (PCB 8+5; PCB 18; PCB 17 and PCB 31+28). This shift towards a lighter pattern is likely a function of greater travel distance from the PCB plant and landfills than the Mars Hill and Edwards sites (1.25 km vs. ~500 m) and a concomitant shift towards lighter congeners that are dominant in the gas phase. This is also the youngest tree sampled, so its exposure is limited in comparison to other trees. In general, the congener patterns observed in tree-bark collected within 1 km of the PCB plant and landfills are very similar, and the variations observed are consistent with what one would expect given distance and direction from the source and the ages of the trees relative to PCB production history.

PCB concentrations in tree bark not only decrease with distance from the PCB plant and landfills (Fig. 2), but the congener patterns also begin to vary to a greater degree. Fig. 4 shows a comparison of Mars Hill (#14) congener pattern to tree bark samples collected 2–8 km east and northeast of the PCB plant site. In general, the same dominant congeners are shared, but due to the much lower total PCB concentration in the more remote samples, the less abundant congeners are below analytical detection limits.

The pattern of variable congener patterns at distance continues at tree #18 (Coldwater). This tree was among the least concentrated and had measurable amounts of only 28 congeners out of 96 reported (Fig. 5). The six most abundant congeners (contributing greater than 5%) were PCB 52 (25-2′5′), PCB 101 (245-2′5′), PCB 99 (245-2′4′), PCB 110 (236-3′4′), PCB 153 + 132 + 105 (mostly 153 which is 245-2′4′5′) and PCB 163 + 138 (primarily 138 which is 234-2′4′5′). These congeners (with the exception of PCB 110) are characteristic of the more persistent PCB congeners in the environment and all of them indicate a dominance by congeners characteristic of Aroclors 1254 and 1260 (Frame et al., 1996).

Tree # 17 (Anniston WWTP) again is a notable exception to the general trend of decreasing concentrations and altered congener patterns with distance away from the

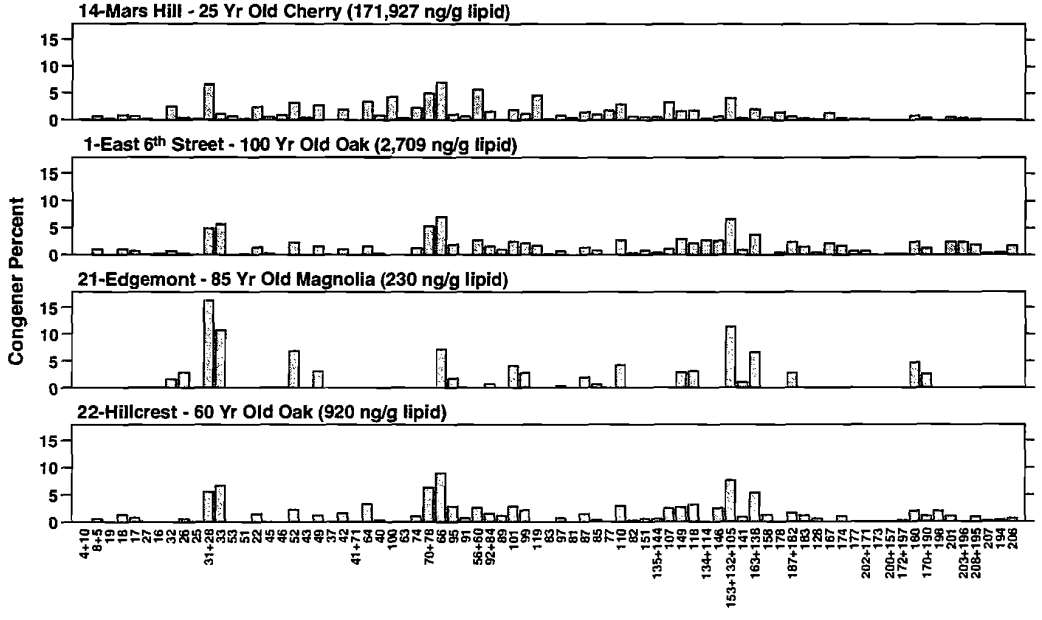

Fig. 4. Percent-of-total PCB congener profile comparisons for four tree bark sites in Anniston, AL: Mars Hill (tree # 14), East Sixth St. (tree #1), Edgemont (tree #21) and Hillcrest (tree #22). Note tree type and age. The congener patterns are not similar ($\cos\theta < 0.80$ for comparisons of tree #14 with #13 and #21).

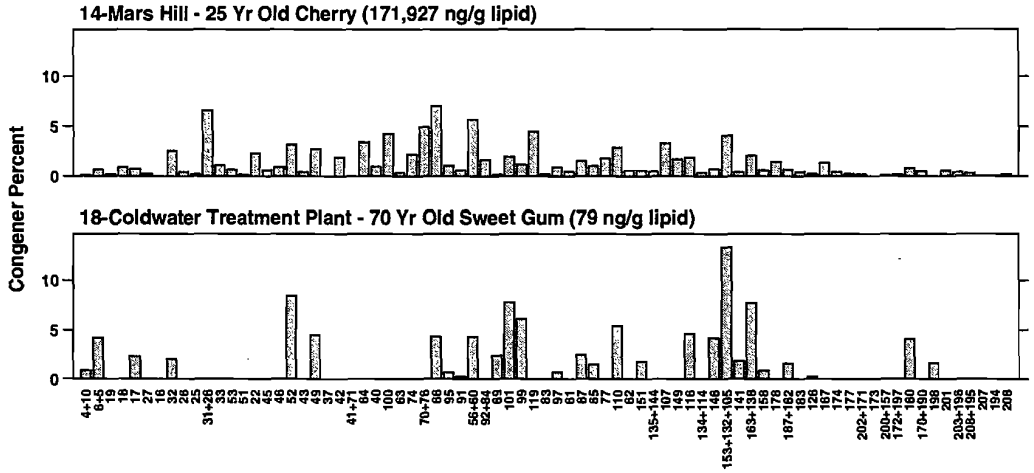

Fig. 5. Percent-of-total PCB congener profile comparisons for two tree bark sites in Anniston, AL: Mars Hill (top, tree #14) and Coldwater treatment plant (bottom, tree #18). Note tree type and age. The congener patterns are not similar ($\cos\theta < 0.80$).

PCB plant site. It is located approximately 6 km south of the PCB plant and landfill (Fig. 1) but it exhibits a congener pattern that is statistically very similar to Mars Hill ($\cos\theta = 0.90$) and is also about the same age (Fig. 6). The high total PCB concentration in the WWTP tree (12 300 ng/g lipid), which is much higher than other samples located this distance from the PCB plant and landfills (600–1000 ng/g lipid), is well within the range of samples collected at Montrose and Edwards, both located within 800 m of the PCB plant (Fig. 1). The PCB impact at this site is high and its source is PCB plant sewage (Coley and Stutz, 1966) and PCB off-gassing from air-dried sewage sludge and the adjacent creeks, both of which have been contaminated with PCBs from surface drainage at the PCB plant and landfills (Tucker, 1970).

3.3. Bark–air comparisons

A comparison of atmospheric gas phase congener distribution between Mars Hill and Carter on August 5, 1997, the date of highest measurement at Mars Hill, shows similarities in the congeners identified but greater representation of light congeners at Carter, particularly 8+5 and 18 (Fig. 7). Mars Hill has about half the percentage of those congeners found at Carter, but has more in the heavier masses particularly in the tetrachlorobiphenyls and into the pentachlorobiphenyls. In spite of these differences, and the order-of-magnitude difference in concentrations, these congener patterns are very similar ($\cos\theta = 0.90$) suggesting that the PCB sources to modern air at these sites are qualitatively alike.

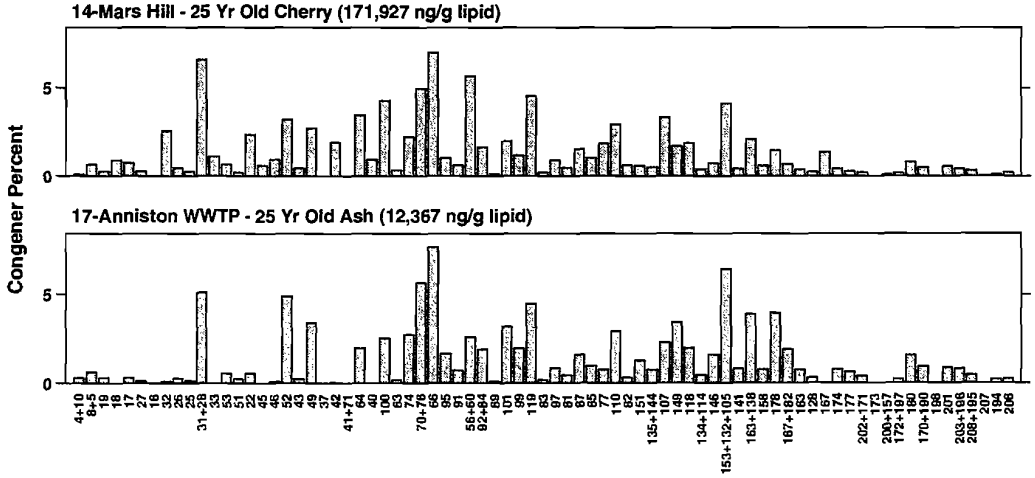

Fig. 6. Percent-of-total PCB congener profile comparisons for tree bark sites in Anniston, AL: Mars Hill (top, tree #14) and the Anniston WWTP (bottom, tree #17). Note tree type and age. The two congener profiles are very similar ($\cos\theta = 0.90$).

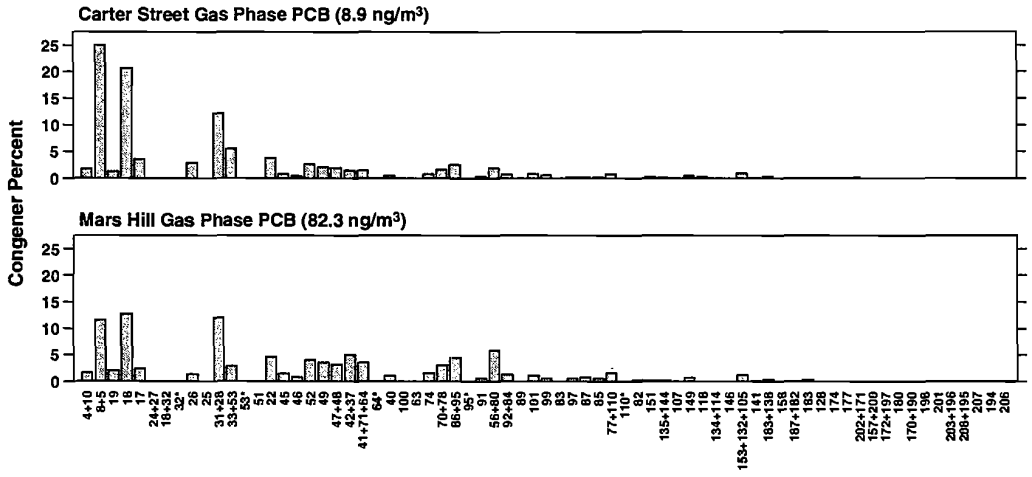

Fig. 7. Percent-of-total PCB congener profile comparisons for two air sampling sites in Anniston, Alabama: Carter (top) and Mars Hill (bottom). The concentration at Mars Hill was maximum for the 1997–98 sampling program collected August 5, 1997. The two congener profiles are very similar ($\cos\theta = 0.90$).

Using average bark and air data from Mars Hill and Carter (Hermanson et al., 2003), the average bark/air total PCB concentration ratio at Mars Hill, the site nearest the plant, is 3904, while at Carter it is 809. The factor of ~5 difference suggests that air concentrations were much higher at Mars Hill at some point in the past than measured in 1997–98. Bark/air ratios were also measured in an earlier study in Bloomington, IN (Hermanson and Hites, 1990). Assuming lipid fractions in Bloomington were the same as the average of all Anniston trees (1.6%), the value at the former WWTP in Bloomington, known to be PCB-contaminated, would be 3687, and the values for two sites without known PCB contamination would be 938. The similarity in values between contaminated and non-contaminated sites in both Anniston and Bloomington suggests similar experiences, and in both cases probably indicates that the highest bark/air ratio sites once had much higher air concentrations that have been reduced by lower PCB emissions to the atmosphere. The expected equilibrium between bark and air, as expressed by K_{oa}, would predict that these ratios are the same everywhere if the air temperature is equal. If that assumption is made, these differences in bark/air ratios indicate that equilibrium is not instantaneous because the ratio is not declining when PCB concentrations in air go down as they likely did at Mars Hill and the Bloomington WWTP after some remediation of PCB waste areas.

4. Conclusions

Results from this study show that tree bark in Anniston is a quantitatively and qualitatively sensitive indicator of PCBs in the atmosphere during the lifetime of the tree. The most concentrated bark sample collected, at Mars Hill (171927 ng/g lipid), is nearest the plant site, but its congener pattern reflects atmospheric conditions when it began growing after the end of PCB production in 1971. While the total PCB concentration is very high and contains concentrations of nearly all congeners analyzed, it is not dominated by a particular group of congeners. It shows clearly that PCB emissions to the atmosphere from sources in Anniston have remained very high and include a large number of congeners. Older trees growing near and downwind from the landfill, which grew during PCB production years, show an unusual presence of high molecular mass PCB apparently from distillation residue, known as Montar, discarded into the landfill at temperatures up to 380 °C. But these trees also have a broad range of congeners similar to Mars Hill. A tree growing near the WWTP shows a congener pattern similar to Mars Hill suggesting that the sources of PCB to each may be similar while the exposure magnitudes are very different. It is likely from bark/air ratios compared between Mars Hill and Carter that the air concentrations in 1997–98 were much lower at Mars Hill than in earlier years (since 1971).

Results from Anniston show that organisms living near the PCB plant and landfills were exposed to very high concentrations of atmospheric PCB and a mixture of PCB congeners that may have included high molecular mass compounds near the plant and landfills. Exposures since the end of production have remained high near that area, but with a different congener blend, in particular not including high molecular mass PCB.

These results are applicable to other sites where PCBs were produced in a high temperature process, and where they were used. Since bark is an effective and sensitive temporal and spatial indicator of exposure to total and congener-specific PCB, the extension of this type of study to other organisms, including humans, would be of significant value in exposure assessment programs.

Acknowledgements

The authors thank J.R. Brozowski, Michelle Donnelly-Kelleher and Cheryl Scholten for skillful assistance in the field and laboratory. We are also grateful to Drs. Laurel Standley and Joel Ressner for their generous assistance.

References

Buehler, S.S., Hites, R.A., 2002. The Great Lakes' integrated atmospheric deposition network. Environ. Sci. Technol. 36, 354A–359A.

Chiarenzelli, J.R., Scrudato, R.J., Arnold, G., Wunderlich, M.L., Rafferty, D., 1996. Volatilization of polychlorinated biphenyls from sediment during drying at ambient conditions. Chemosphere 33, 899–911.

Chiarenzelli, J., Scrudato, R., Wunderlich, M., 1997. Volatile loss of PCB Aroclors from subaqueous sand. Environ. Sci. Technol. 31, 597–602.

Chiarenzelli, J.R., Bush, B., Case, A., Barnard, E., Smith, B., O'Keefe, P., Gilligan, E., Johnson, G., 2000. Defining the sources of airborne polychlorinated biphenyls: evidence for the influence of microbially dechlorinated congeners from river sediment. Can. J. Fish. Aquat. Sci. 57 (Supp 1), 86–94.

Clarkson, P.J., Larrazabal-Moya, D., Staton, I., McLeod, C.W., Ward, D.B., Sharifi, V.N., Swithenbank, J., 2002. The use of tree bark as a passive sampler for polychlorinated dibenzo-*p*-dioxins and furans. Int. J. Environ. Anal. Chem. 82, 843–850.

Coley, G., Stutz, C.N., 1966. Treatment of parathion wastes and other organics. J. Water Pollut. Control Fed. 38, 1345–1349.

Durfee, R.L., Contos, G., Whitmore, F.C., Barden, J.D., Hackman, E.E., III, Westin, R.A., 1976. PCBs in the United States – industrial use and environmental distribution. US Environmental Protection Agency, EPA Publication 560/6-76-005:88. Washington, DC.

Edelblut, C.M., 1957. Toxicity of Montars. Memorandum to R.S. Wobus. Anniston, AL. Bates No. MONS 095660.

Frame, G.M., Cochran, J.W., Bøwadt, S.S., 1996. Complete PCB congener distributions for 17 Aroclor mixtures determined by 3 HRGC systems optimized for comprehensive, quantitative congener-specific analysis. J. High Res. Chromatog. 19, 657–668.

Hermanson, M.H., Hites, R.A., 1989. Long-term measurements of atmospheric polychlorinated biphenyls in the vicinity of Superfund dumps. Environ. Sci. Technol. 23, 1253–1258.

Hermanson, M.H., Hites, R.A., 1990. Polychlorinated biphenyls in tree bark. Environ. Sci. Technol. 24, 666–671.

Hermanson, M.H., Scholten, C.A., Compher, K., 2003. Variable air temperature response of gas-phase atmospheric polychlorinated biphenyl concentrations near a former production facility. Environ. Sci. Technol. 37, 4038–4042.

Johnson, G.W., Quensen III, J.F., Chiarenzelli, J., Hamilton, C., 2006. Polychlorinated Biphenyl Compounds (PCBs). In: Morrison, R., Murphy, B. (Eds.), Environmental Forensics: A Contaminant Specific Guide. Elsevier, Amsterdam, pp. 187–225.

Magar, V.S., Johnson, G.W., Brenner, R., Durell, G., Quensen III, J.F., Foote, E., Ickes, J.A., Peven-McCarthy, C., 2005. Long-term recovery of PCB-contaminated sediments at the Lake Hartwell Superfund Site: PCB dechlorination i – end-member characterization. Environ. Sci. Technol. 39, 3538–3547.

Meredith, M.L., Hites, R.A., 1987. Polychlorinated biphenyl accumulation in tree bark and wood growth rings. Environ. Sci. Technol. 21, 709–712.

Miller, M.M., Ghodbane, S., Wasik, S.P., Tewari, Y.B., Martire, D.E., 1984. Aqueous solubilities, octanol/water partition coefficients, and entropies of melting of chlorinated benzenes and biphenyls. J. Chem. Eng. Data. 29, 184–190.

Peck, A.M., Hornbuckle, K.C., 2005. Gas-phase concentrations of current use pesticides in Iowa. Environ. Sci. Technol. 39, 2952–2959.

Ramsey, F.D., 1970. Aroclor losses to the atmosphere at the HCl scrubber jet. Memorandum to E.G. Wright. Bates No. DSW 014031.

Rushneck, D., Beliveau, A., Fowler, B., Hamilton, C., Hoover, D., Kaye, K., Berg, M., Smith, T., 2004. Concentrations of dioxin-like PCB congeners in unweathered Aroclors by HRGC/HRMS using EPA Method 1668A. Chemosphere 54, 79–87.

Schulz, H., Popp, P., Huhn, G., Stärk, H-J., Schüürmann, G., 1999. Biomonitoring of airborne inorganic and organic pollutants by means of pine tree barks. I. Temporal and spatial variations. Sci. Total Environ. 232, 49–58.

Simonich, S., Hites, R.A., 1995. Global distribution of persistent organochlorine compounds. Science 269 (5232), 1851–1854.

Tucker, E.S., 1970. PCB content of Choccolocco Creek fish. Memorandum to W. B. Papageorge. Bates Nos. 013504–013506.

US Environmental Protection Agency, 1979. Potential Hazardous Waste Site Inspection Report, EPA Region 4, Site 19, Anniston, AL.

US Environmental Protection Agency, 2001. Final Summary Report of Technical Review and Evaluation of Potential PCB Releases: Anniston PCB Site, Anniston, Alabama. Office of Emergency & Remedial Response, Washington.

Williams, M.J., Haupt, V.R., Moody, R.G., 1966. Standard Operating Instructions for Aroclors. Anniston, AL. Bates Nos. DSW 001572–DSW 001586.

Wright, E.G., 1970a. Aroclor loses at the Anniston Plant. Progress Report No. 2, Technical Services Department, Anniston, AL. Bates No. DSW 013202.

Wright, E.G., 1970b. PCB levels in ambient air at Anniston Plant. Memorandum to W.B. Papageorge. Anniston, AL. Bates No. DSW 014061.

Zhang, X., Schramm, K-W., Henkelmann, B., Klimm, C., Kuane, A., Kettrup, A., Lu, P., 1999. A method to estimate the octanol–air partition coefficient of semivolatile organic compounds. Anal. Chem. 71, 3834–3838.

Zhu, L., Hites, R., 2006. Brominated flame retardants in tree bark from North America. Environ. Sci. Technol. 40, 3711–3716.