

**REVERSIBLE AND IRREVERSIBLE ADSORPTION OF
NAPHTHALENE AND α -NAPHTHOL TO SOIL**

by

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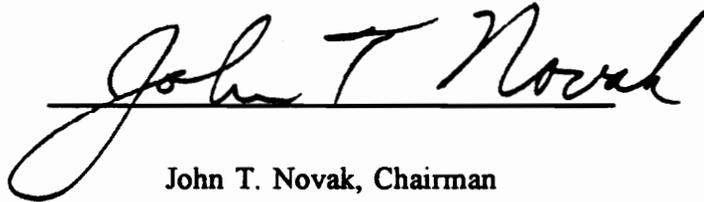
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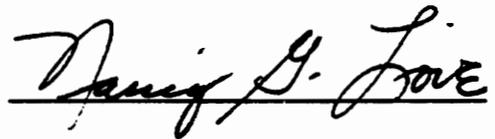
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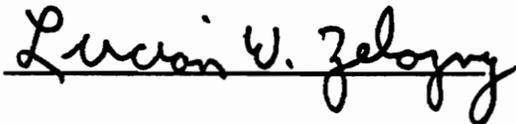
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(ABSTRACT)

Experiments were performed with naphthalene and α -naphthol to compare the processes involved in the sorption of a polycyclic aromatic hydrocarbon (PAH) and its metabolite, respectively, and to assess the bioavailability of these two compounds adsorbed to two sandy soils with different organic carbon contents. Adsorption conditions were varied to estimate the extent that biologically-mediated and chemically-induced oxidative coupling, and rate-limited diffusive processes contributed to the apparent irreversible adsorption of these compounds. The purposes of this research were to: (1) investigate the processes which cause the irreversible adsorption of organic contaminants to soil; (2) gauge the impact that these different adsorption processes have on the bioavailability of sorbed contaminants; and, (3) evaluate the environmental significance of these processes in soils and the subsurface. This dissertation has been prepared as three separate articles for publication in peer reviewed journals. The first article serves as a literature review in evaluating the significance of oxidative coupling reactions in soil and subsurface environments. This review concludes that oxidative coupling of organic contaminants may be important in soils and could be stimulated as a viable remediation strategy. For subsurface systems oxidative coupling appears much more limited, however, engineered systems could be developed to enhance this process. The second article presents experimental results used to quantify the individual processes involved in the irreversible adsorption of naphthalene and α -naphthol. This article concludes that both biological and chemical catalysts are important in promoting irreversible adsorption reactions, and that once the

partial oxidation of a PAH occurs, oxidative coupling can become a significant process affecting contaminant fate. The third and final article examines the effect of different adsorption processes on the subsequent bioavailability of sorbed naphthalene and α -naphthol, and concludes that the biodegradation of naphthalene and α -naphthol adsorbed to both the soils tested was controlled by the rate of desorption and the reversibility of the adsorption process.

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to examine the amount and distribution of these reactive elements in soils and the subsurface, and evaluate the environmental significance of oxidative coupling on the fate of organic contaminants based on this information.

IRREVERSIBLE ADSORPTION PROCESSES

Organic contaminants are adsorbed to various soil fractions by a number of different adsorption mechanisms. Thorough reviews of these processes have been summarized elsewhere (4), while this review will focus on the irreversible adsorption of substituted aromatic compounds. The binding of a susceptible organic contaminant to the soil matrix can be formed through condensation reactions (oxidative coupling) with SOM, or through strong electrostatic charge transfer complexes formed between a charged contaminant and an oppositely charged solid surface (ie. chemisorption). Oxidative coupling reactions (Figure 1) may be chemically induced by metal oxides (5) or clay minerals (6), or biologically mediated by extracellular soil enzymes (7). Biologically-mediated oxidative coupling is analogous to humic substance formation reactions. Extracellular oxidoreductases use molecular oxygen (O_2) or hydrogen peroxide (H_2O_2) to oxidize phenolic compounds to reactive quinones or free radicals. Aromatic amines are also susceptible to oxidative coupling. The reactivity of phenolic compounds or anilines with these enzymes is increased by the addition of electron donating (ie. $-OH$, $-NH_2$) substituents, and decreased by the addition of electron withdrawing (ie. $-Cl$, $-NO_2$) substituents (8). Under certain conditions, reactive functional groups of SOM can undergo nonbiological autoxidation to form quinones (2). These reactive species can then participate in polymerization reactions which form covalent linkages between the contaminant and SOM. Because the oxidized species generated by these enzymes are highly reactive, the subsequent binding reactions are non-specific.

below the surface horizon may be because a number of soil organisms can produce catecholoxidase. However, this study (27) was conducted within an organically rich drained histosol and may not be reflective of phenoloxidase activity within deeper mineral soils.

OXIDATIVE COSUBSTRATES

In well aerated surface soils the availability of O₂ for oxidative coupling reactions should not be limiting. However, oxygen can be considered a "scavenged" element due to its consumption in metabolic processes and reactions with reduced metals, and the amount of O₂ likely decreases with depth in the soil column. Oxygen also has a slow diffusion rate into and low solubility in saturated soils, and anoxic microsites may develop in well aerated, saturated soils (29). Even within unsaturated soils, the presence of anoxic microsites have been detected at low pore water pressures (< -4 kPa) (30). Oxygen penetration depths into lake sediments are also generally shallow, often restricted to the first few millimeters (31). The reduction of oxygen in deep or saturated soils will likely reduce the extent of oxidative coupling reactions in these environments.

Natural sources of hydrogen peroxide in soil include photochemical formation, percolation with rainwater, and production from fungal and bacterial species. In surface environments the major source of H₂O₂ may be photochemical formation (32). Average H₂O₂ concentrations in rainwater range between 0.1 to 10 μM (33), well below the concentrations used in many oxidative coupling experiments (ca. 1000 μM) (8). A number of soil bacteria (34) and fungi (35) release H₂O₂ through normal metabolic processes. Hydrogen peroxide concentrations measured in culture medium produced by *Aerococcus* bacteria ranged from 31 to 217 μM (34). The white rot fungus *Phanerochaete chrysosporium* contains a glucose oxidase enzyme which provides the H₂O₂ for lignin peroxidase activity (35). The production of H₂O₂ from

the presence/absence of peroxidase and phenoloxidase under the different experimental conditions were unsuccessful and the direct measurement of these enzymatic activities was unproven. The reduction in biological activity evidenced by TLC analyses may reflect a general decrease in enzymatic activity and has been used as a general indicator of extracellular oxidoreductase activity. The transformation of α -naphthol under non-coupling conditions may be caused by chemical reactions with mineral surfaces.

If biologically-mediated coupling reactions were reduced under Anoxic-Biotic and Oxic-Abiotic conditions, then chemically-induced processes must have accounted for the majority of irreversibly sorbed material under these conditions. Qualitative, high magnification SEM analyses of these soils positively identified a number of iron and titanium oxides. Qualitative, elemental topology was determined with lower magnification SEM analyses and revealed that roughly 5% (molar basis) of the soil surfaces were coated with metal oxides (Table 1). Therefore, a catalytic amount of metal oxides may have been present in this soil to account for the observed irreversible adsorption. The reductive dissolution mechanism proposed by Stone (25) suggests that adsorption of the organic contaminant onto the metal oxide must first occur. The limited surface areas that these oxides provide in the sandy soils studied may have contributed to the observed concentration effect.

Naphthalene desorption isotherms with the high organic soil are shown in Figure 6 (d). The waterwash procedure was unable to remove a portion of the sorbed naphthalene, however, solvent extraction was able to recover virtually all of the remaining material ($Q_{IRR}/Q_{eq} = 0.016-0.024$). Thus naphthalene adsorption was nearly fully reversible and showed no concentration effect on irreversible adsorption. TLC analyses also revealed that no transformation of naphthalene occurred, corresponding to the fact that the

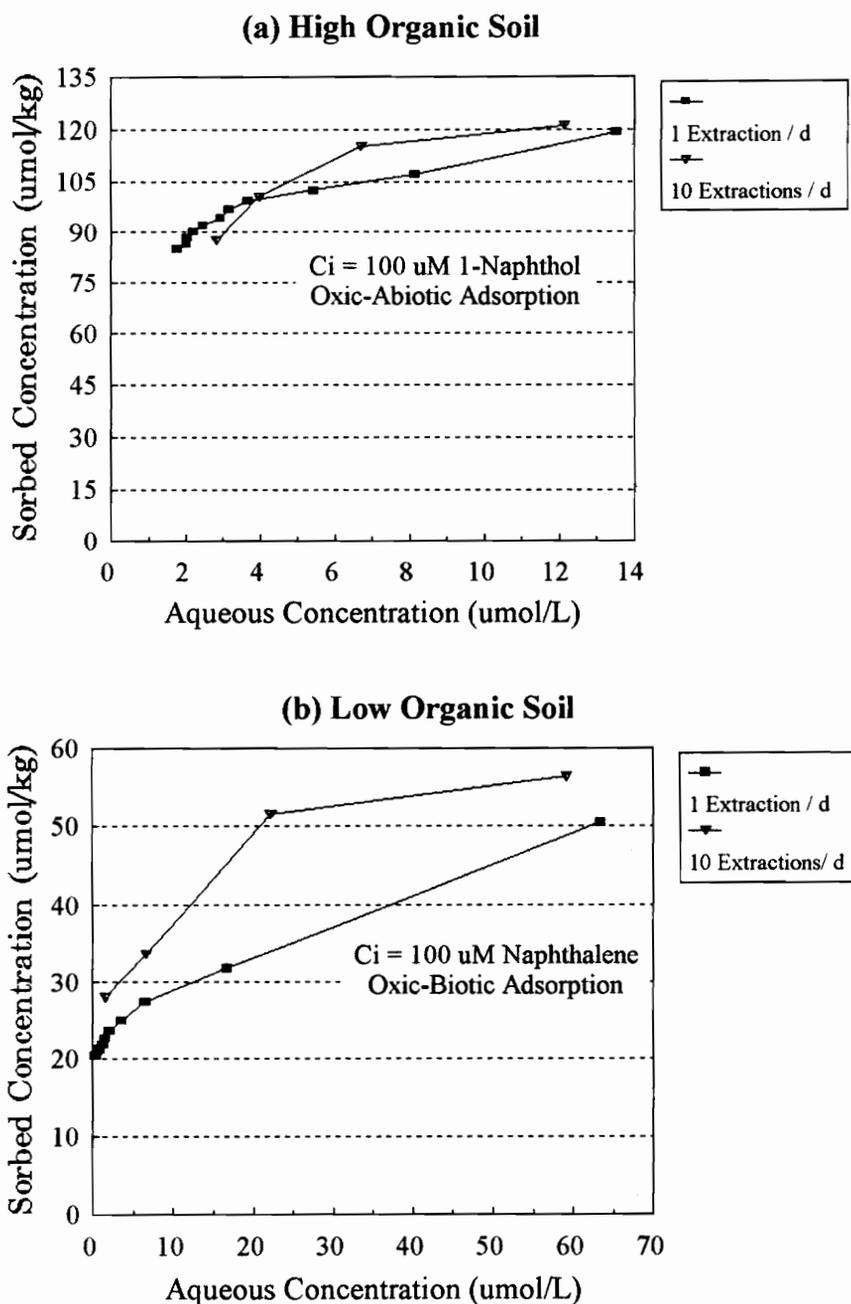


Figure 14. Impact of desorption kinetics on waterwashed desorption isotherms. Upper right data point represents 2 d adsorption equilibrium, lower left data point represents sorbed concentration after tenth water extraction

have been because the absence of oxygen limited oxidative adsorption processes. The reduced adsorption under Oxidic-Abiotic conditions may have been caused by the autoclaving procedure which could have reduced the reactivity of the SOM. Under Oxidic-Biotic conditions 39.2% of Q_{eq} of α -naphthol was removed during the waterwashing procedure. For the non-coupling conditions 61.6-66.3% of Q_{eq} of α -naphthol was recovered by waterwashing. These data are consistent with the results obtained with the high organic soil. Only 71.4% of Q_{eq} of naphthalene was removed from this soil by waterwashing, apparently because of rate-limited diffusive processes. The incomplete recovery of nonreactive naphthalene and the desorption hysteresis observed within the low organic soil may have been due to intraparticle diffusion (36).

Bioavailability of α -Naphthol

The bioavailability of sorbed α -naphthol and naphthalene was determined by the addition of acclimated naphthalene degraders to the 2 d equilibrium soil reactors (Unwashed Microcosms) and to the set which had undergone the complete fill-and-draw water extraction (Waterwashed Microcosms). Biodegradation of the test compounds was confirmed by $^{14}CO_2$ evolution and TLC analyses of the final supernatant solutions which revealed metabolite production. Because the mass balance recoveries were unsatisfactory based on $^{14}CO_2$ measurements (44-69%), the final sorbed concentrations measured by sample combustion have been used as a gauge of the biologically unavailable fraction. These recoveries were probably low because passive $^{14}CO_2$ traps were used, instead of active traps which are purged with air. However, the final sorbed concentrations determined by sample combustion were a direct measure of the remaining material and were therefore the most accurate estimates of the unavailable fraction.

The results of the bioavailability studies for α -naphthol with the high organic soil are shown in Figure 15. Another group of reactors which had undergone the

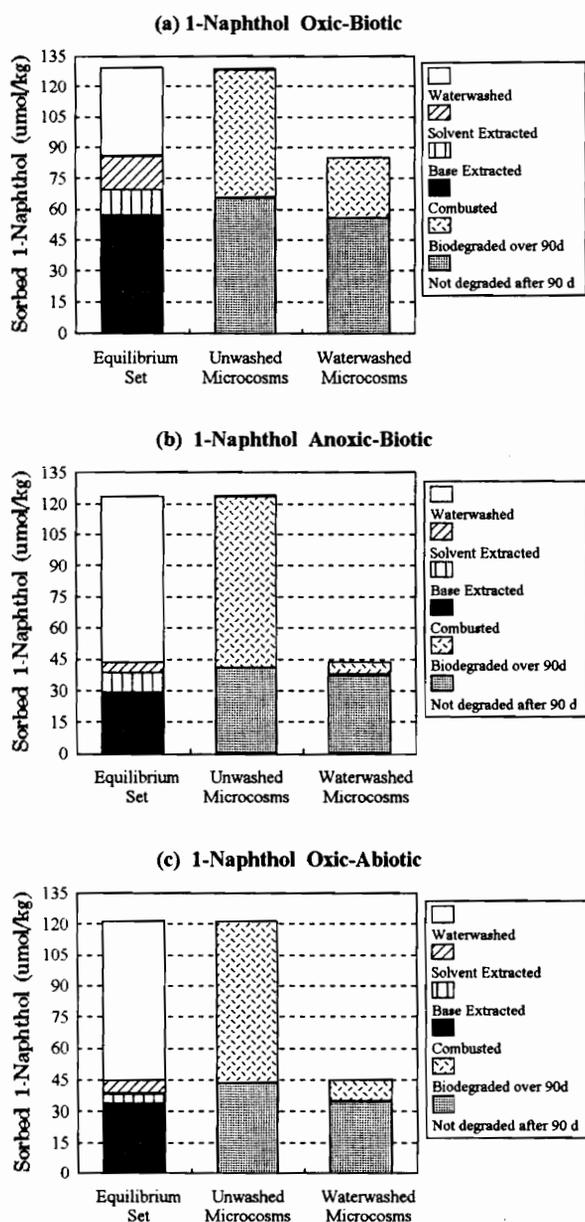


Figure 15. Bioavailability of 1-naphthol adsorbed to high organic soil under different equilibrium conditions. Equilibrium Set refers to soil reactors which had undergone complete extraction analysis where "irreversibly" sorbed material was defined as fraction remaining after solvent extraction. Unwashed Microcosms were seeded after the 2 d equilibrium period and Waterwashed Microcosms were seeded after the waterwashing procedure

waterwashing procedure were carried through immediate, multiple solvent extractions (Equilibrium Set). Irreversibly adsorbed material was operationally defined as the amount of activity remaining after the fifth and final solvent extraction (Q_{IRR}). This set then underwent a base extraction before the soil was combusted. For the Oxic-Biotic condition (Figure 15(a)), the final sorbed concentrations for the both microcosm sets after the 90 d incubation period were less than the operationally defined irreversibly adsorbed value of $69.4 \mu\text{mol}\cdot\text{kg}^{-1}$. After 90 days, organisms within the unwashed set reduced the sorbed concentration to $65.4 \mu\text{mol}\cdot\text{kg}^{-1}$, while organisms within the waterwashed set attained a final sorbed concentration of $55.9 \mu\text{mol}\cdot\text{kg}^{-1}$. These results suggest that Q_{IRR} determined by solvent extraction overestimated the amount of "irreversibly" sorbed material. Desorption kinetics during waterwashing (up to 10 extractions per day) may have had a minor effect on the recovery of sorbed activity, but was probably not a factor during solvent extractions (1 extraction per day). Instead, some of the nondesorbable material probably became bioavailable during the incubation period. Hsu and Bartha (1976) (24) reported that a portion of DCA recovered from soil by base extraction was bioavailable over incubation periods up to 190 days. The further reduction of the sorbed concentration within the waterwashed microcosms compared to the unwashed sets suggests, however, that biodegradation was limited by the rate of desorption.

For the Anoxic-Biotic and Oxic-Abiotic conditions (Figures 15 (b) and (c), respectively), the final sorbed concentrations for each microcosm set after 90 d of biodegradation were very similar to Q_{IRR} . These results suggest that under non-coupling conditions the operationally defined measure of Q_{IRR} was an excellent estimate of the biologically unavailable fraction. However, the term "available" should be applied cautiously because no attempt was made to maximize degradation (ie. nutrient addition), and degradation rates are also known to be slow at very low substrate concentrations (7). The reduced bioavailability of sorbed α -naphthol under

Oxic-Biotic conditions corresponded directly to the greater amount of irreversible adsorption. Biologically-mediated and chemically-induced oxidative coupling reactions could occur under these conditions. While all these adsorption reactions may not have been irreversible (as evidenced by final sorbed concentrations less than Q_{IRR}), the strength of these interactions appeared to greatly limit bioavailability. For the other two conditions the primary irreversible adsorption process was believed to be chemically-induced oxidative coupling catalyzed by metal oxide surfaces. The bioavailability data obtained under these conditions suggest that these irreversible adsorption reactions resulted in nearly complete contaminant unavailability.

The impact of rate-limited desorption on the bioavailability of α -naphthol in the low organic soil appeared greater compared to the other soil (Figure 16). For the unwashed microcosms the final sorbed concentration attained after biodegradation was always greater than Q_{IRR} , yet always less for the waterwashed sets. The operationally defined Q_{IRR} under Oxic-Biotic conditions was $24.2 \mu\text{mol}\cdot\text{kg}^{-1}$, but within the corresponding biologically active systems the final sorbed concentrations measured after the 90 d degradation period were 30.0 and $18.6 \mu\text{mol}\cdot\text{kg}^{-1}$ for the unwashed and waterwashed sets, respectively. These same trends between the unwashed and waterwashed sets were also seen under the non-coupling conditions. The reduction in the sorbed concentration in the waterwashed microcosms below that obtained in the unwashed sets suggests that rate-limited desorption controlled biodegradation within this soil. These results also show that Q_{IRR} consistently overestimated the actual irreversible component under all conditions in this soil. Unlike the high organic soil, desorption kinetic limitations were observed during the waterwashing of this soil and may have had an effect on the recovery of sorbed material and the estimate of Q_{IRR} . With the unwashed microcosms, distinct differences in the bioavailability of α -naphthol (Figure 16) and naphthalene (Figure 17 (b)) sorbed to the low organic soil were observed. The biological reduction of sorbed α -naphthol was significantly less

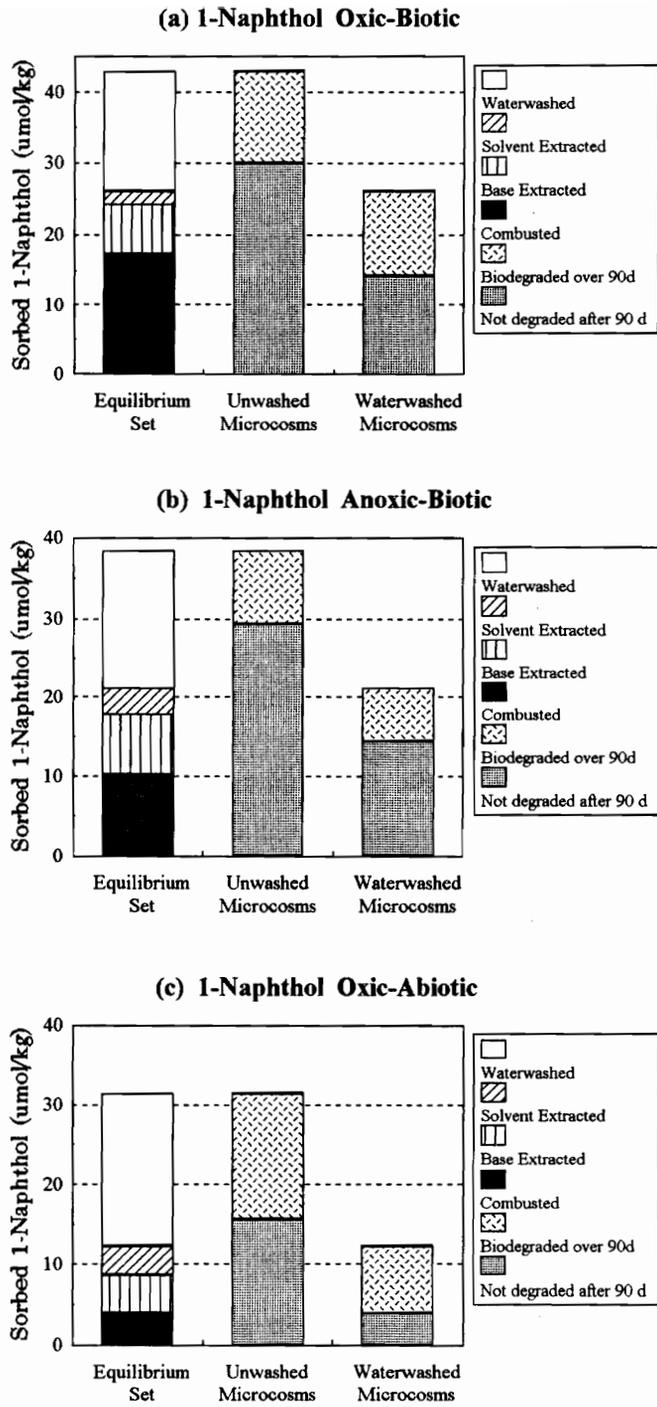


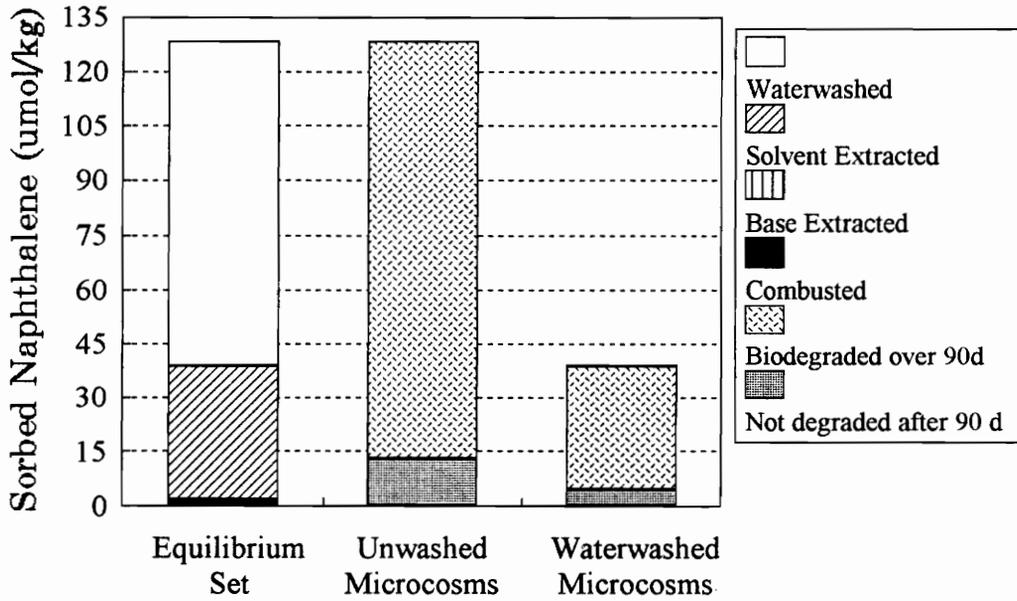
Figure 16. Bioavailability of 1-naphthol adsorbed to low organic soil under different equilibrium conditions.

than for naphthalene. These data imply that rate-limited desorption of α -naphthol was a more significant process than estimated by naphthalene results, and may have been caused by differences in the effective diffusivities of naphthalene and α -naphthol within this soil. The addition of the -OH group to α -naphthol increases the structural complexity, and reactivity of this compound. As sorbate structure complexity increases, diffusion is constrained and a greater diffusion-limited desorption response is expected (37). Because a significant amount of contaminant adsorption to the low organic soil was believed to occur in interstitial sites, the differences between the sorbate structure and reactivity of naphthalene and α -naphthol may have an even greater effect on desorption kinetics. The larger α -naphthol molecule may also have a lower effective diffusivity due to constrictivity within extremely small pores (38). The -OH group may also allow α -naphthol to adsorb to polar mineral surfaces within the pores and be subject to surface diffusion processes.

Bioavailability of Naphthalene

Naphthalene bioavailability results in the high and low organic soils are presented in Figure 17. The further biodegradation of sorbed naphthalene within the waterwashed microcosms compared to the unwashed sets for both soils suggests that degradation was controlled by the rate of desorption. For the high organic soil, organisms within either microcosm set could not reduce the sorbed concentration below Q_{IRR} . The higher measure of irreversibly sorbed naphthalene within the microcosms may be due to the oxidative coupling of susceptible metabolites. As shown in the first paper of this series, the irreversible adsorption of naphthalene to the high organic soil as a function of contact time was studied (33). These results showed that the extractability of naphthalene decreased as contact time increased, and TLC analyses of the supernatants showed the production of a more polar metabolite after 30 days. Naphthalene adsorbed to the low organic soil was also readily bioavailable. Even though naphthalene metabolites could also have been involved in oxidative coupling

(a) Naphthalene High Organic Soil



(b) Naphthalene Low Organic Soil

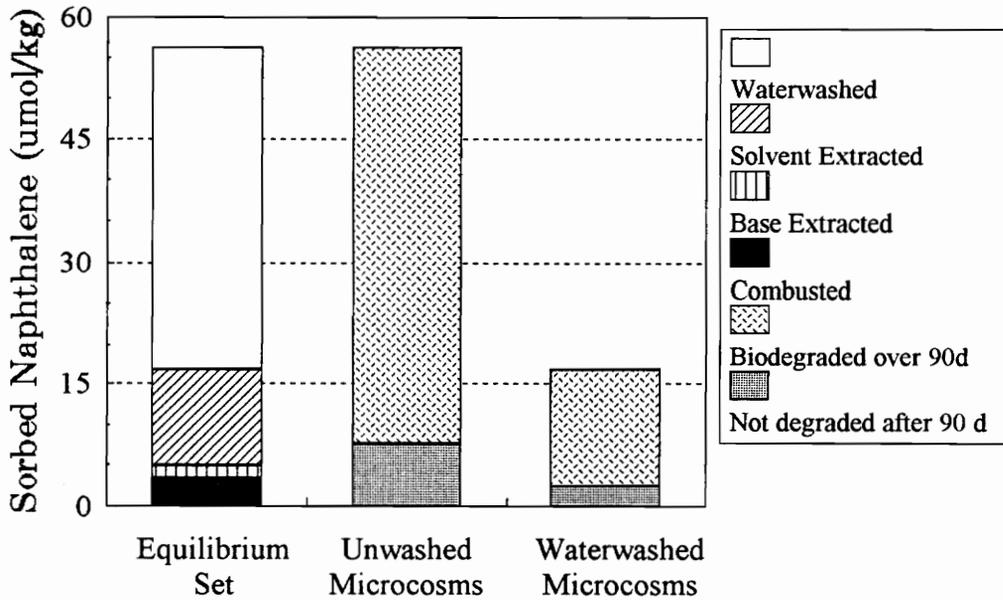


Figure 17. Bioavailability of naphthalene adsorbed to high and low organic soils under Oxidic-Biotic equilibrium conditions.

reactions in this soil, the lower amount of organic matter may have reduced the opportunity for these reactions to occur. These results have important implications regarding competitive processes between further biodegradation and irreversible adsorption. For PAH degradation in mineral soils, the reduction in the amount of reactive SOM may decrease binding and therefore promote degradation. However for organic soils, after the initial oxidation of a PAH occurs irreversible adsorption may become a significant process affecting contaminant fate.

Effect of Adsorption Processes on Bioavailability

To estimate the contribution of individual processes involved in the irreversible adsorption of α -naphthol to these two soils the principle of superposition was used. The superposition of individual adsorption mechanisms has been proposed by Weber *et.al* (1992) for different soil components (39). As described in the first paper of this series (33), an attempt was made to differentiate Q_{IRR} from the portion of material chemisorbed (Q_{CHEM}) by subtracting the fraction trapped in rate-limited diffusive mass transfer adsorptive sites (Q_{DIFF}) where:

$$Q_{CHEM} = Q_{IRR} - Q_{DIFF} \quad (3).$$

The percentage of irreversibly bound naphthalene measured with the Equilibrium Sets was used to estimate Q_{DIFF} for α -naphthol based on the equilibrium sorbed (Q_{eq}) value. With the high organic soil $Q_{DIFF} = 0.02 \cdot Q_{eq}$, and with the low organic soil $Q_{DIFF} = 0.08 \cdot Q_{eq}$ (33). For the high organic soil the estimate of Q_{DIFF} ranged from 2.42-2.57 $\mu\text{mol} \cdot \text{kg}^{-1}$ for the three conditions tested. Subtracting this quantity from Q_{IRR} measured under Oxidic-Biotic, Anoxic-Biotic and Oxidic-Abiotic conditions yields Q_{CHEM} values of 66.8, 35.9 and 35.8 $\mu\text{mol} \cdot \text{kg}^{-1}$, respectively. These chemisorbed concentrations estimated from the extraction procedures were in good agreement with the bioavailability results. For the waterwashed microcosms the final sorbed concentrations after 90 d of biodegradation were 55.9, 37.4 and 34.6 $\mu\text{mol} \cdot \text{kg}^{-1}$ for these three conditions, respectively. Under Oxidic-Biotic conditions, the biological

reduction of the sorbed concentration below Q_{IRR} suggests that Q_{CHEM} may have been overestimated based solely on the extraction procedures employed. Because the estimates of Q_{DIFF} were in agreement with the non-coupling results, this estimate should also have been valid under Oxidic-Biotic conditions. Therefore, the difference between Q_{IRR} determined by solvent extraction or by biodegradation experiments was probably due to the bioavailability of even strongly sorbed α -naphthol.

For the low organic soil the estimate of Q_{DIFF} ranged from 2.51-3.43 $\mu\text{mol}\cdot\text{kg}^{-1}$. Subtracting this quantity from Q_{IRR} measured under Oxidic-Biotic, Anoxic-Biotic and Oxidic-Abiotic conditions yields Q_{CHEM} values of 20.8, 10.0 and 6.3 $\mu\text{mol}\cdot\text{kg}^{-1}$, respectively. The final sorbed concentrations in the waterwashed microcosms after the biodegradation period were 18.6, 12.9 and 5.0 $\mu\text{mol}\cdot\text{kg}^{-1}$ for these three conditions, respectively. Therefore, the fraction of α -naphthol chemisorbed to the low organic soil based on the extraction procedures was also a reasonable estimate of the unavailable fraction under all conditions. These results suggest that the amount of material trapped within mass transfer-limited sites must be accounted for to accurately estimate the biologically unavailable fraction.

As already noted, the extent of rate-limited diffusive processes (Q_{DIFF} estimated from naphthalene results) were first separated from chemisorption processes. General comparisons made between the different experimental conditions can then be used to estimate the extent of biologically-mediated and chemically-induced oxidative coupling. Under Oxidic-Abiotic conditions the operative irreversible adsorption process was probably chemically induced, while under Oxidic-Biotic conditions both processes likely occurred. The results obtained under Anoxic-Biotic conditions varied considerably for both soils. With the high organic soil little biological coupling appeared to take place under anoxic conditions, while with the low organic soil biological coupling appeared significant. Therefore the difference between Q_{CHEM}

calculated for the Oxidic-Biotic and Oxidic-Abiotic conditions was used to estimate the extent of biologically-mediated oxidative coupling by the following relationship:

$$Q_{\text{CHEM}} = Q_{\text{BIO}} + Q_{\text{MINERAL}} \quad (4)$$

where Q_{BIO} is the irreversibly sorbed concentration due to biological coupling and Q_{MINERAL} is the irreversibly sorbed concentration due to chemically-induced coupling reactions with soil mineral surfaces. Irreversibly sorbed concentrations measured and calculated through this adsorption superposition procedure based on the bioavailability results are listed in Table 4 and summarized in Figure 18. For comparison purposes, the results obtained based solely on the Equilibrium Set extraction procedures are also included.

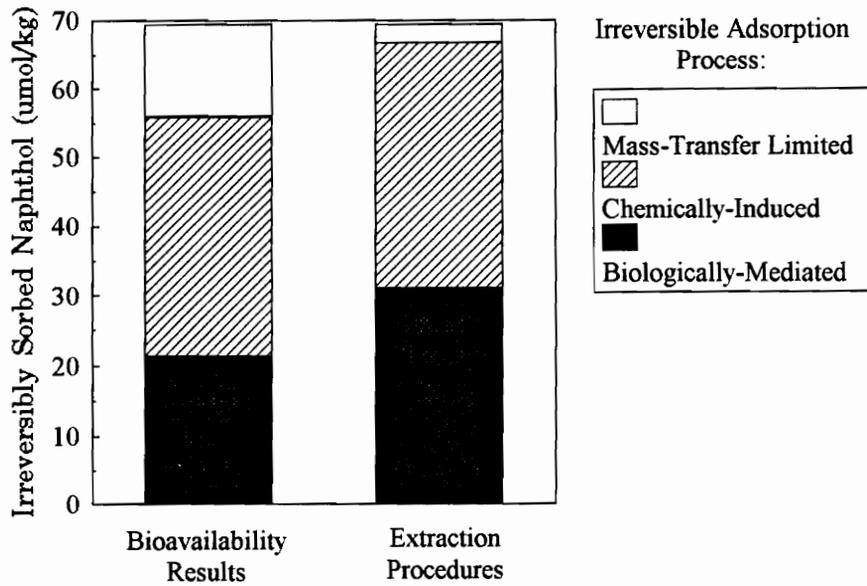
Based on the bioavailability results obtained with the high organic soil, biologically-mediated and chemically-induced oxidative coupling were responsible for 30.7% and 49.8% of Q_{IRR} , respectively. Rate-limited diffusive processes accounted for 19.5% of Q_{IRR} . Based on the extraction procedures, biologically-mediated and chemically-induced oxidative coupling were responsible for 44.7% and 51.6% of Q_{IRR} , respectively, and rate-limited diffusive processes accounted for 3.7% of Q_{IRR} in the high organic soil. Based on the bioavailability results obtained with the low organic soil, biologically-mediated and chemically-induced oxidative coupling were responsible for 56.2% and 20.7% of Q_{IRR} , respectively. Rate-limited diffusive processes accounted for 23.1% of Q_{IRR} . Based on the extraction procedures with the low organic soil, biologically-mediated and chemically-induced oxidative coupling were responsible for 59.9% and 26.0% of Q_{IRR} , respectively, and rate-limited diffusive processes accounted for 14.1% of Q_{IRR} . These results suggest that the solvent extraction procedure tended to overestimate the contribution of biological coupling and underestimate the contribution of rate-limited diffusive processes involved in the apparent irreversible adsorption of α -naphthol. The amount of material trapped within mass transfer-limited sites must be accounted for to accurately estimate the biologically unavailable fraction.

Table 4. Summary of α -Naphthol Irreversible Adsorption Concentrations under Oxid-Biotic Conditions based on Bioavailability Results and Extraction Procedures.^a

Analysis Based On:	HIGH ORGANIC SOIL:					
	C_{eq} ($\mu\text{mol/L}$)	Q_{eq} ($\mu\text{mol/kg}$)	Q_{IRR} ($\mu\text{mol/kg}$)	Q_{CHEM} ($\mu\text{mol/kg}$)	Q_{BIO} ($\mu\text{mol/kg}$)	$Q_{MINERAL}$ ($\mu\text{mol/kg}$)
Bioavailability	6.94	128	69.4	55.9	21.3	34.6
Solvent Extractions	6.94	128	69.4	66.8	31.0	35.8
Analysis Based On:	LOW ORGANIC SOIL:					
	C_{eq} ($\mu\text{mol/L}$)	Q_{eq} ($\mu\text{mol/kg}$)	Q_{IRR} ($\mu\text{mol/kg}$)	Q_{CHEM} ($\mu\text{mol/kg}$)	Q_{BIO} ($\mu\text{mol/kg}$)	$Q_{MINERAL}$ ($\mu\text{mol/kg}$)
Bioavailability	68.9	42.9	24.2	18.6	13.6	5.0
Solvent Extractions	68.9	42.9	24.2	20.8	14.5	6.3

^a C_{eq} Equilibrium Aqueous Concentration measured after 2 day contact time
 Q_{eq} Equilibrium Sorbed Concentration measured after 2 day contact time
 Q_{IRR} Irreversibly Sorbed Concentration measured after final solvent extraction under Oxid-Biotic conditions
 Q_{CHEM} Chemisorbed Concentration measured after 90 d biodegradation in Oxid-Biotic Waterwashed Microcosms, or calculated by equation (1) for extraction set
 Q_{BIO} Biologically-Mediated Chemisorbed Concentration calculated by equation (2)
 $Q_{MINERAL}$ Irreversibly Sorbed Concentration measured after 90 d biodegradation in Oxid-Abiotic Waterwashed Microcosms, or measured after final solvent extraction under Oxid-Abiotic conditions

(a) High Organic Soil



(b) Low Organic Soil

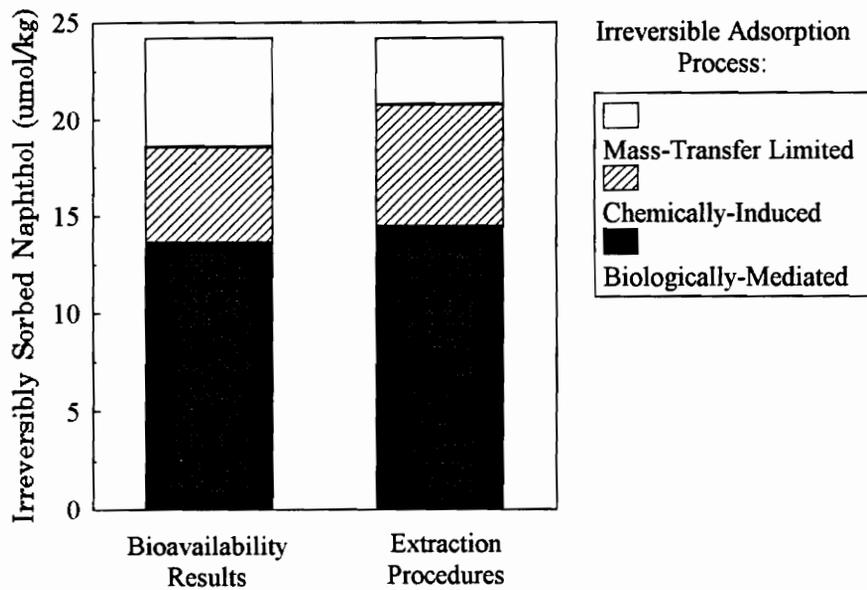


Figure 18. Relative contributions of individual processes responsible for the irreversible adsorption of 1-naphthol based on contaminant bioavailability and extraction procedures

SUMMARY AND CONCLUSIONS

Experiments were performed to assess the bioavailability of α -naphthol and naphthalene adsorbed to two sandy soils with different organic carbon contents. The biodegradation of these compounds was controlled by the rate of desorption and the reversibility of the adsorption processes. Both biologically-mediated and chemically-induced oxidative coupling reactions were significant irreversible adsorption processes that greatly limited contaminant bioavailability. The desorption of α -naphthol appeared to be even more rate-limited than naphthalene due to the increased structural complexity and reactivity provided by the addition of the -OH group. Greater rate-limited desorption of α -naphthol occurred within the low organic soil, presumably due to more binding within interstitial sites.

A separate set of experiments used a series of sequential extraction procedures to estimate the amount of α -naphthol and naphthalene irreversibly sorbed to the two soils. The principle of superposition was applied to the results obtained with these extraction procedures and the bioavailability experiments to determine the contribution of individual processes involved in the adsorption of α -naphthol. After accounting for material trapped within rate-limited adsorptive sites, the final sorbed concentration remaining after the multiple solvent extraction procedure yielded reasonable estimates of the biologically unavailable fraction. The solvent extraction procedure tended to overestimate the contribution of biological coupling and underestimate the contribution of rate-limited diffusive processes involved in the apparent irreversible adsorption of α -naphthol.

The results obtained with naphthalene revealed important implications regarding competitive processes between further biodegradation and irreversible adsorption. For PAH degradation in mineral soils, the reduction in the amount of reactive soil organic matter may decrease binding and therefore promote degradation. However for organic

soils, after the initial oxidation of a PAH occurs irreversible adsorption may become a significant process affecting contaminant fate.

REFERENCES

1. Cerniglia, C.E., VanBaalen, C. and Gibson, D.T. (1980) Metabolism of Naphthalene by *Cyanobacterium Oscillatoria* sp., Strain JCM. *J. Gen. Microbiol.* 116:405-494.
2. Heitkamp, M.A., Freeman, J.P. and Cerniglia, C.E. (1987). Naphthalene Biodegradation in Environmental Microcosms: Estimates of Degradation Rates and Characterization of Metabolites. *Appl. Environ. Microbiol.* 53:129-136.
3. Kiyohara, H. and Nagao, K. (1978) The Catabolism of Phenanthrene and Naphthalene by Bacteria. *J. Gen. Microbiol.* 105:69-75.
4. Cerniglia, C.E. and Gibson, D.T. (1977) Metabolism of naphthalene by *Cunninghamella elegans*. *Appl. Environ. Microbiol.* 34:363-370.
5. Ferris, J.P., Fasco, M.J., Stylianopoulou, F.L., Jerina, D.M., Daly, J.W. and Jeffrey, A.M. (1973) Mono-oxygenase activity in *Cunninghamella bainieir*. evidence for a fungal system similar to liver microsomes. *Arch. Biochem. Biophys.* 156:97-103.
6. Sutherland, J.B. (1992). Detoxification of polycyclic aromatic hydrocarbons by fungi. *J. Ind. Microbiol.* 9:53-62.
7. Boethling, R.S. and Alexander, M. (1979). Effect of Concentration of Organic Chemicals on Their Biodegradation by Natural Microbial Communities. *Appl. Environ. Microbiol.* 37:1211-1216.
8. Bollag, J.-M., Czaplicki, E.J. and Minard, R.D. (1975) Bacterial Metabolism of 1-Naphthol. *J. Agric. Food Chem.* 23:85-90.
9. Mihelcic and Luthy (1988a). Degradation of Polycyclic Aromatic Hydrocarbon Compounds Under Various Redox Conditions in Soil-Water Systems. *Appl. Environ. Microbiol.* 54:1182-1187.
10. Mihelcic and Luthy (1988b). Microbial Degradation of Acenaphthene and Naphthalene under Denitrification Conditions in Soil-Water Systems. *Appl. Environ. Microbiol.* 54:1188-1198.
11. Knezovich, J.P., Harrison, F.L. and Wilhelm, R.G. (1987). The Bioavailability of Sediment-Sorbed Organic Chemicals: A Review. *Water, Air and Soil Pollution* 32:233-245.

12. Kukkonen, J., McCarthy, J.F. and Oikari, A. (1991). Binding and bioavailability of organic micropollutants in natural waters: effects of the quality and the quantity of dissolved organic matter. In *Organic Substances and Sediments in Water, Vol. 3*. Lewis Pub. Inc., Chelsea, MI.
13. Robinson, K.G., Farmer, W.S. and Novak, J.T. (1990). Availability of sorbed toluene in soils for biodegradation by acclimated bacteria. *Water Research*. 24:345-350.
14. Dec, J. and J.-M. Bollag. (1988) Microbial release and degradation of catechol and chlorophenols bound to synthetic humic acid. *Soil Sci. Soc. Am. J.* 52:1366-1371.
15. Robinson, K.G. and Novak, J.T. (1990). Bioavailability of chlorinated phenols sorbed to dissolved organic matter. Proceedings, AWWA Cincinnati, OH, June 1990.
16. Rijnaarts, H.H.M., Bachumann, S., Jumelet, J.C. and Zehnder, A.J.G. (1990). Effect of Desorption and Intraparticle Mass Transfer on the Aerobic Biomineralization of α -Hexachlorocyclohexane in a Contaminated Calcareous Soil. *Environ. Sci. Technol.* 24:1349-1354.
17. Mihelcic, J.R. and Luthy, R.G. (1991). Sorption and Microbial Degradation of Naphthalene in Soil-Water Suspensions Under Denitrification Conditions. *Environ. Sci. Technol.* 25:169-177.
18. Ogram, A.V., Jessup, R.E., Ou, L.T. and Rao, P.S.C. (1985). Effects of Sorption on Biological Degradation Rates of (2,4-Dichlorophenoxy) Acetic Acid in Soils. *Appl. Environ. Microbiol.* 49:582-587
19. Guerin, W.F. and Boyd, S.A. (1992). Differential Bioavailability of Soil-Sorbed Naphthalene to Two Bacterial Species. *Appl. Environ. Microbiol.* 58:1142-1152.
20. Calderbank, A. (1989). The Occurrence and Significance of Bound Pesticide Residues in Soil. *Rev. Environ. Contam. Toxicol.* 108:71-103.
21. Steinberg, S.M., Pignatello, J.J. and Sawhney, B.L. (1987) Persistence of 1,2-Dibromoethane in Soils: Entrapment in Micropores. *Environ. Sci. Technol.* 21:1201-1208.

22. Scribner, S.L., Benzing, T.R., Sun, S. and Boyd, S.A. (1992) Desorption and Bioavailability of Aged Simazine Residues in Soil from a Continuous Corn Field. *J. Environ. Qual.* 21:115-120.
23. Remberger, M., Alland, A.-S. and Neilson, A.H. (1986) Biotransformations of Chloroguaiacols, Chlorocatechols, and Chloroveratroles in Sediments. *Appl. Environ. Microbiol.* 51:552-588.
24. Hsu, T.S. and Bartha, H. (1976). Hydrolyzable and nonhydrolyzable 3,4-dichloroaniline-humus complexes and their respective rates of degradation. *J. Agric. Food Chem.* 24:118-122.
25. Martin, J.P. and Haider, K. (1971). Microbial Activity in Relation to Soil Humus Formation. *Soil Science.* 111:54-63.
26. Bollag, J.M., Liu, S.Y. and Minard, R.D. (1980) Cross-Coupling of Phenolic Humus Constituents and 2,4-Dichlorophenol. *Soil Sci. Soc. Am. J.* 44:52-56.
27. Suflita, J.M. and Bollag, J.-M. (1981) Polymerization of Phenolic Compounds by a Soil-Enzyme Complex. *Soil Sci. Soc. Am. J.* 45:297-302.
28. Martin, J.P. and K. Haider. (1976) Decomposition of specifically ¹⁴C-labeled ferulic acid: free and linked into model humic acid-type polymers. *Soil Sci. Soc. Am. J.* 40:377-380.
29. Wolf, D.C and J.P. Martin. (1976) Decomposition of fungal mycelia and humic-type polymers containing ¹⁴C from ring and sidechain labeled 2,4-D and chloroprotham. *Soil Sci. Soc. Am. J.* 40:700-704.
30. Bollag, J.-M. (1992). Decontaminating soil with enzymes. *Environ. Sci. Technol.* 26:1876-1881.
31. Stone, A. and Morgan, J.J. (1987) In *Aquatic Surface Chemistry*; Stumm, W. Ed.; Wiley; New York.
32. Stone, A.T. and Morgan, J.J. (1984) Reduction and dissolution of manganese (III) and manganese (IV) oxides by organics. 1. Reaction with hydroquinone. *Environ. Sci. Technol.* 18:450-456.
33. Burgos, W.D. and Novak, J.T. (1995) Reversible and Irreversible Adsorption of Naphthalene and α -Naphthol to Soil: 1. Elucidation of Processes. *Preceding article*

34. Petruska, J.A., Mullins, D.E., Young, R.W. and Collins, E.R. (1985) A Benchtop System For Evaluation of Pesticide Disposal by Composting. *Nuclear and Chem. Waste Manag.* 5:177-182.
35. Brusseau, M.L., Jessup, R.E. and Rao, P.S.C. (1991). Nonequilibrium Sorption of Organic Chemicals: Elucidation of Rate-Limiting Processes. *Environ. Sci. Technol.* 25:134-142.
36. Wu, S.-C. and Gschwend, P.M. (1986) Sorption Kinetics of Hydrophobic Organic Compounds to Natural Sediments and Soils. *Environ. Sci. Technol.* 20:717-725.
37. Brusseau, M.L. and Rao, P.S.C. (1991). Influence of Sorbate Structure on Nonequilibrium Sorption of Organic Compounds. *Environ. Sci. Technol.* 25:1501-1506.
38. Ball, W.P. and Roberts, P.V. (1991). Long-Term Sorption of Halogenated Organic Chemicals by Aquifer Material. 2. Intraparticle Diffusion. *Environ. Sci. Technol.* 25:1237-1249.
39. Weber, W.J., McGinley, P.M., and Katz, L.E. (1992). A Distributed Reactivity Model for Sorption by Soils and Sediments. 1. Conceptual Basis and Equilibrium Assessments. *Environ. Sci. Technol.* 26:1955-1962.

APPENDIX I. ADSORPTION ISOTHERM RESULTS

**1-Naphthol with High Organic Soil
Oxic-Biotic Adsorption Conditions**

Ceq (umol/L)	Qeq (umol/kg)	LINEAR REGRESSION		
0.37	13.30			
0.45	13.18			
0.59	12.98			
6.47	129.10			
6.60	128.90			
7.75	127.30			
42.86	216.86			
87.73	706.93			
115.66	944.39			
152.40	1169.70			
153.90	1167.60			
		Regression Output:		
		Constant	0.00	
		Std Err of Y Est	58.43	
		R Squared	0.98	
		No. of Observations	11.00	
		Degrees of Freedom	10.00	
		X Coefficient(s)	7.73	<--- Kd
		Std Err of Coef.	0.22 241.72	<--- Koc
			2.38	<--- log Koc
LOG Ceq	LOG Qeq	FREUNDLICH ISOTHERM LOG-LOG LINEAR REGRESSION		
-0.43	1.12			
-0.35	1.12			
-0.23	1.11			
0.81	2.11			
0.82	2.11			
0.89	2.10			
1.63	2.34			
1.94	2.85			
2.06	2.98			
2.18	3.07			
2.19	3.07			
		Regression Output:		
		Constant	1.40	<--- Kf
		Std Err of Y Est	0.12	
		R Squared	0.98	
		No. of Observations	11.00	
		Degrees of Freedom	9.00	
		X Coefficient(s)	0.75	<---- n
		Std Err of Coef.	0.04	

**1-Naphthol with High Organic Soil
Anoxic-Biotic Adsorption Conditions**

Ceq (umol/L)	Qeq (umol/kg)
0.82	12.66
0.85	12.62
10.03	124.20
10.73	123.20
180.20	1131.40
235.80	1054.60

LINEAR REGRESSION

Regression Output:			
Constant		0.00	
Std Err of Y Est		124.02	
R Squared		0.95	
No. of Observations		6.00	
Degrees of Freedom		5.00	
X Coefficient(s)		5.16	<--- Kd
Std Err of Coef.	0.42	161.09	<--- Koc
		2.21	<--- log

LOG Ceq	LOG Qeq
-0.09	1.10
-0.07	1.10
1.00	2.09
1.03	2.09
2.26	3.05
2.37	3.02

**FREUNDLICH ISOTHERM
LOG-LOG LINEAR REGRESSION**

Regression Output:			
Constant		1.20	<--- Kf
Std Err of Y Est		0.08	
R Squared		0.99	
No. of Observations		6.00	
Degrees of Freedom		4.00	
X Coefficient(s)		0.81	<---- n
Std Err of Coef.		0.03	

**1-Naphthol with High Organic Soil
Oxic-Abiotic Adsorption Conditions**

Ceq (umol/L)	Qeq (umol/kg)
0.71	12.82
0.98	12.45
10.78	123.10
13.51	119.40
186.20	1123.00
200.50	1103.40

LINEAR REGRESSION

Regression Output:

Constant		0.00	
Std Err of Y Est		46.18	
R Squared		0.99	
No. of Observations		6.00	
Degrees of Freedom		5.00	
X Coefficient(s)		5.76	<--- Kd
Std Err of Coef.	0.17	180.13	<--- Koc
		2.26	<--- log

LOG Ceq	LOG Qeq
-0.15	1.11
-0.01	1.10
1.03	2.09
1.13	2.08
2.27	3.05
2.30	3.04

**FREUNDLICH ISOTHERM
LOG-LOG LINEAR REGRESSION**

Regression Output:

Constant		0.93	<--- Kf
Std Err of Y Est		0.13	
R Squared		0.98	
No. of Observations		6.00	
Degrees of Freedom		4.00	
X Coefficient(s)		0.95	<---- n
Std Err of Coef.		0.06	

**1-Naphthol with Low Organic Soil
Oxic-Biotic Adsorption Conditions**

Ceq (umol/L)	Qeq (umol/kg)
5.28	6.51
5.70	5.94
68.88	42.94
147.40	72.59
489.92	151.92
609.86	262.39
754.80	338.38
794.20	284.00

LINEAR REGRESSION

Regression Output:			
Constant		0.00	
Std Err of Y Est		27.20	
R Squared		0.96	
No. of Observations		8.00	
Degrees of Freedom		7.00	
X Coefficient(s)		0.40	<--- Kd
Std Err of Coef.	0.02	76.25	<--- Koc
		1.88	<--- log

LOG Ceq	LOG Qeq
0.72	0.81
0.76	0.77
1.84	1.63
2.17	1.86
2.69	2.18
2.79	2.42
2.88	2.53
2.90	2.45

**FREUNDLICH ISOTHERM
LOG-LOG LINEAR REGRESSION**

Regression Output:			
Constant		0.21	<--- Kf
Std Err of Y Est		0.07	
R Squared		0.99	
No. of Observations		8.00	
Degrees of Freedom		6.00	
X Coefficient(s)		0.78	<---- n
Std Err of Coef.		0.03	

**1-Naphthol with Low Organic Soil
Anoxic-Biotic Adsorption Conditions**

Ceq (umol/L)	Qeq (umol/kg)
5.93	5.61
68.14	43.97
76.39	32.59
752.10	342.10

LINEAR REGRESSION

Regression Output:			
Constant		0.00	
Std Err of Y Est		7.76	
R Squared		1.00	
No. of Observations		4.00	
Degrees of Freedom		3.00	
X Coefficient(s)		0.46	<--- Kd
Std Err of Coef.	0.01	87.72	<--- Koc
		1.94	<--- log

LOG Ceq	LOG Qeq
0.77	0.75
1.83	1.64
1.88	1.51
2.88	2.53

**FREUNDLICH ISOTHERM
LOG-LOG LINEAR REGRESSION**

Regression Output:			
Constant		0.05	<--- Kf
Std Err of Y Est		0.11	
R Squared		0.99	
No. of Observations		4.00	
Degrees of Freedom		2.00	
X Coefficient(s)		0.85	<---- n
Std Err of Coef.		0.07	

**1-Naphthol with Low Organic Soil
Oxic-Abiotic Adsorption Conditions**

Ceq (umol/L)	Qeq (umol/kg)
7.59	3.32
75.35	34.06
79.25	28.64
826.70	239.10

LINEAR REGRESSION

Regression Output:

Constant		0.00	
Std Err of Y Est		7.78	
R Squared		0.99	
No. of Observations		4.00	
Degrees of Freedom		3.00	
X Coefficient(s)		0.29	<--- Kd
Std Err of Coef.	0.01	56.00	<--- Koc
		1.75	<--- log

LOG Ceq	LOG Qeq
0.88	0.52
1.88	1.53
1.90	1.46
2.92	2.38

**FREUNDLICH ISOTHERM
LOG-LOG LINEAR REGRESSION**

Regression Output:

Constant		-0.25	<--- Kf
Std Err of Y Est		0.06	
R Squared		1.00	
No. of Observations		4.00	
Degrees of Freedom		2.00	
X Coefficient(s)		0.91	<---- n
Std Err of Coef.		0.04	

**Naphthalene with High Organic Soil
Oxic-Biotic Adsorption Conditions**

Ceq (umol/L)	Qeq (umol/kg)	LINEAR REGRESSION			
0.08	1.27				
0.10	1.24	Regression Output:			
0.53	13.07	Constant	0.00		
0.81	12.69	Std Err of Y Est	9.63		
0.85	12.63	R Squared	0.97		
1.04	26.17	No. of Observations	12.00		
4.82	76.14	Degrees of Freedom	11.00		
5.87	129.90	X Coefficient(s)	18.19	<--- Kd	
6.58	128.92	Std Err of Coef.	0.59	568.59	<--- Koc
7.10	128.20			2.75	<--- log
7.35	127.80				
7.68	127.40				

LOG Ceq	LOG Qeq	FREUNDLICH ISOTHERM LOG-LOG LINEAR REGRESSION			
-1.09	0.10				
-1.00	0.09	Regression Output:			
-0.28	1.12	Constant	1.25	<--- Kf	
-0.09	1.10	Std Err of Y Est	0.09		
-0.07	1.10	R Squared	0.99		
0.02	1.42	No. of Observations	11.00		
0.68	1.88	Degrees of Freedom	9.00		
0.77	2.11	X Coefficient(s)	1.05	<---- n	
0.82	2.11	Std Err of Coef.	0.04		
0.85	2.11				
0.87	2.11				

**Naphthalene with Low Organic Soil
Oxic-Biotic Adsorption Conditions**

Ceq (umol/L)	Qeq (umol/kg)
0.46	0.75
0.52	0.66
4.23	7.96
4.34	7.81
8.78	15.49
33.44	36.65
47.95	44.22
55.12	61.93
63.21	50.77

LINEAR REGRESSION

Regression Output:

Constant		0.00
Std Err of Y Est		5.94
R Squared		0.94
No. of Observations		9.00
Degrees of Freedom		8.00
X Coefficient(s)		0.96 <--- Kd
Std Err of Coef.	0.06	185.16 <--- Koc
		2.27 <--- log

LOG Ceq	LOG Qeq
-0.34	-0.13
-0.28	-0.18
0.63	0.90
0.64	0.89
0.94	1.19
1.52	1.56
1.68	1.65
1.74	1.79
1.80	1.71

**FREUNDLICH ISOTHERM
LOG-LOG LINEAR REGRESSION**

Regression Output:

Constant	0.21	<--- Kf
Std Err of Y Est	0.11	
R Squared	0.98	
No. of Observations	9.00	
Degrees of Freedom	7.00	
X Coefficient(s)	0.89	<---- n
Std Err of Coef.	0.05	

APPENDIX II. WATERWASHED DESORPTION ISOTHERM RESULTS

**1-Naphthol with High Organic Soil
Oxic-Biotic Adsorption Conditions**

Ci = 1000 uM			Ci = 100 uM			Ci = 10 uM		
sample	C (umol/L)	Q (umol/kg)	C (umol/L)	Q (umol/kg)	C (umol/L)	Q (umol/kg)	C (umol/L)	Q (umol/kg)
eq	153.94	1167.57	6.94	128.42	0.47	13.15		
fd1	98.17	1077.48	4.67	123.79	0.24	12.90		
fd2/5	47.74	898.67	2.35	113.72	0.09	12.42		
fd6/10	22.87	787.10	0.95	107.48	0.04	12.04		
fd11/15	13.00	719.92	0.53	103.11	0.03	11.72		
fd16/20	6.99	679.80	0.31	99.76	0.02	11.44		
fd21/30	3.22	633.50	0.17	94.29	0.01	10.93		
fd31/40	1.37	603.85	0.09	89.60	0.01	10.43		
fd41/50	0.99	577.62	0.07	85.11	0.01	9.96		
solv1	0.00	477.03	0.00	76.56	0.00	9.34		
solv5	0.00	376.20	0.00	69.40	0.00	8.81		

Sample ID: eq = 2 d adsorption equilibrium sample
 fd2/5 = pooled sample from fill-and-draw extractions #2-5
 solv5 = sorbed concentration remaining after fifth solvent extraction

**1-Naphthol with High Organic Soil
Anoxic-Biotic Adsorption Conditions**

sample	Ci = 1000 uM		Ci = 100 uM		Ci = 10 uM	
	C (umol/L)	Q (umol/kg)	C (umol/L)	Q (umol/kg)	C (umol/L)	Q (umol/kg)
eq	208.00	1092.96	10.38	123.68	0.84	12.65
fd1	98.98	1006.87	7.28	117.11	0.57	12.55
fd2/5	62.60	788.90	4.95	99.24	0.39	11.09
fd6/10	36.97	627.71	3.10	85.25	0.24	9.99
fd11/15	16.55	443.99	1.50	68.09	0.13	8.55
fd16/20	5.63	307.86	0.63	53.15	0.05	7.24
fd21/30	2.23	256.02	0.27	47.16	0.02	6.70
fd31/40	1.72	239.77	0.13	44.24	0.01	6.40
fd41/50	1.05	229.36	0.09	43.44	0.01	6.32
solv1	0.00	210.63	0.08	42.76	0.01	6.25
solv5	0.00	184.00	0.00	38.40	0.00	5.19

**1-Naphthol with High Organic Soil
Oxic-Abiotic Adsorption Conditions**

sample	Ci = 1000 uM		Ci = 100 uM		Ci = 10 uM	
	C (umol/L)	Q (umol/kg)	C (umol/L)	Q (umol/kg)	C (umol/L)	Q (umol/kg)
eq	193.40	1113.11	12.15	121.23	0.84	12.63
fd1	80.30	1040.25	6.70	115.11	0.48	12.12
fd2/5	55.29	839.58	3.97	100.60	0.31	10.76
fd6/10	38.75	663.81	2.82	87.70	0.22	9.54
fd11/15	24.80	551.31	1.91	78.97	0.15	8.69
fd16/20	18.07	469.32	1.48	72.20	0.12	7.99
fd21/30	10.44	374.60	0.92	63.83	0.07	7.04
fd31/40	6.02	319.94	0.60	58.38	0.05	6.32
fd41/50	3.80	285.49	0.40	44.72	0.04	5.75
solv1	0.00	269.78	0.00	41.78	0.00	5.50
solv5	0.00	152.00	0.00	38.30	0.00	4.85

1-Naphthol with Low Organic Soil

Ci = 100 uM		Ci = 100 uM		Ci = 100 uM		
Oxic-Biotic Adsorption Conditions		Anoxic-Biotic Adsorption Conditions		Oxic-Abiotic Adsorption		
sample	C (umol/L)	Q (umol/kg)	C (umol/L)	Q (umol/kg)	C (umol/L)	Q (umol/kg)
eq	68.88	42.94	72.26	38.28	77.28	31.35
fd1	10.21	37.93	12.27	31.58	15.87	22.82
fd2/5	3.95	28.28	4.76	21.19	4.33	13.51
fd6/10	0.40	27.07	1.42	17.31	1.00	12.16
fd11/15	0.15	26.63	0.44	16.10	0.37	11.66
fd16/20	0.14	26.20	0.40	15.55	0.33	11.21
fd21/30	0.13	26.12	0.31	15.13	0.25	10.88
fd31/40			0.30	14.70	0.22	10.58
solv1	0.00	24.93	0.00	13.60	0.00	10.30
solv5	0.00	24.16	0.00	13.09	0.00	8.84

**Naphthalene with High Organic Soil
Oxic-Biotic Adsorption Conditions**

sample	Ci = 100 uM		Ci = 10 uM		Ci = 1 uM	
	C (umol/L)	Q (umol/kg)	C (umol/L)	Q (umol/kg)	C (umol/L)	Q (umol/kg)
eq	7.18	128.09	0.83	12.66	0.09	1.25
fd1	4.04	124.24	0.35	12.31	0.03	1.22
fd2/5	3.49	110.77	0.31	11.08	0.03	1.10
fd6/10	3.09	95.70	0.25	9.81	0.03	0.96
fd11/15	2.38	83.79	0.20	8.77	0.02	0.86
fd16/20	1.96	73.75	0.16	7.88	0.02	0.77
fd21/30	1.49	57.86	0.13	6.40	0.02	0.62
fd31/40	0.95	46.71	0.09	5.31	0.01	0.52
fd41/50	0.62	38.56	0.06	4.46	0.01	0.44
solv1	0.00	21.90	0.00	3.13	0.00	0.31
solv5	0.00	2.10	0.00	0.31	0.00	0.03

**Naphthalene with Low Organic Soil
Oxic-Biotic Adsorption Conditions**

C_i = 100 uM

sample	C (umol/L)	Q (umol/kg)
eq	59.17	56.35
fd1	22.19	51.52
fd2/5	6.62	33.66
fd6/10	1.52	27.99
fd11/15	0.50	25.67
fd16/20	0.40	23.64
fd21/30	0.23	20.72
fd31/40	0.20	18.02
fd41/50	0.08	16.09
solv1	0.00	6.49
solv5	0.00	4.82

APPENDIX III. 14C-SORBED ACTIVITY DISTRIBUTION RESULTS

**1-Naphthol with High Organic Soil
Oxic-Biotic Adsorption Conditions**

Sorbed Concentration Remaining After:	Waterwash Procedure Ci = 1000 uM		Waterwash Procedure Ci = 100 uM		Waterwash Procedure Ci = 10 uM	
	C (umol/L)	Q (umol/kg)	C (umol/L)	Q (umol/kg)	C (umol/L)	Q (umol/kg)
2d adsorption equilibrium	153.94	1167.57	7.75	127.30	0.37	13.30
final waterwash	0.99	577.62	0.07	85.11	0.01	9.96
final solvent extraction	0.00	412.00	0.00	62.50	0.00	7.57
final base extraction	0.00	284.20	0.00	45.30	0.00	5.33
Solvent Extraction Procedure						
	Ci = 1000 uM		Ci = 100 uM		Ci = 10 uM	
2d adsorption equilibrium	152.40	1169.70	6.60	128.90	0.45	13.18
final waterwash	NA	NA	NA	NA	NA	NA
final solvent extraction	0.00	340.40	0.00	76.30	0.00	9.97
final base extraction	0.00	329.60	0.00	68.90	0.00	8.06
Solvent Extraction Procedure						
	Ci = 1000 uM		Ci = 100 uM		Ci = 10 uM	
2d adsorption equilibrium			0.59	12.98		
final waterwash			NA	NA		
final solvent extraction			0.00	8.86		
final base extraction			0.00	8.36		

**1-Naphthol with High Organic Soil
Anoxic-Biotic Adsorption Conditions**

	Waterwash Procedure		Waterwash Procedure		Waterwash Procedure	
Sorbed Concentration	Ci = 1000 uM		Ci = 100 uM		Ci = 10 uM	
Remaining After:	C (umol/L)	Q (umol/kg)	C (umol/L)	Q (umol/kg)	C (umol/L)	Q (umol/kg)
2d adsorption equilibrium	180.20	1131.40	10.73	123.20	0.85	12.62
final waterwash	1.05	229.36	0.09	43.44	0.01	6.32
final solvent extraction	0.00	170.20	0.00	37.30	0.00	5.16
final base extraction	0.00	116.50	0.00	29.70	0.00	3.95
	Solvent Extraction Procedure		Solvent Extraction Procedure		Solvent Extraction Procedure	
	Ci = 1000 uM		Ci = 100 uM		Ci = 10 uM	
2d adsorption equilibrium	235.80	1054.60	10.03	124.20	0.82	12.66
final waterwash	NA	NA	NA	NA	NA	NA
final solvent extraction	0.00	198.60	0.00	39.40	0.00	5.22
final base extraction	0.00	156.40	0.00	27.60	0.00	2.81

**1-Naphthol with High Organic Soil
Oxic-Abiotic Adsorption Conditions**

Sorbed Concentration Remaining After:	Waterwash Procedure Ci = 1000 uM		Waterwash Procedure Ci = 100 uM		Waterwash Procedure Ci = 10 uM			
	C (umol/L)	Q (umol/kg)	C (umol/L)	Q (umol/kg)	C (umol/L)	Q (umol/kg)		
2d adsorption equilibrium	200.50	1103.40	13.51	119.40	0.98	12.45		
final waterwash	3.80	285.49	0.40	44.72	0.04	5.75		
final solvent extraction	0.00	139.60	0.00	38.50	0.00	4.78		
final base extraction	0.00	105.10	0.00	33.00	0.00	4.11		
			Solvent Extraction Procedure Ci = 1000 uM		Solvent Extraction Procedure Ci = 100 uM		Solvent Extraction Procedure Ci = 10 uM	
2d adsorption equilibrium	186.20	1123.00	10.78	123.10	0.71	12.82		
final waterwash	NA	NA	NA	NA	NA	NA		
final solvent extraction	0.00	164.30	0.00	38.10	0.00	2.87		
final base extraction	0.00	154.30	0.00	33.40	0.00	2.13		

**1-Naphthol with Low Organic Soil
Oxic-Biotic Adsorption Conditions**

Sorbed Concentration Remaining After:	Waterwash Procedure		Waterwash Procedure		Waterwash Procedure	
	Ci = 1000 uM	C (umol/L)	Q (umol/kg)	Ci = 100 uM	C (umol/L)	Q (umol/kg)
2d adsorption equilibrium				68.88	42.94	
final waterwash			0.13	0.00	26.12	
final solvent extraction			0.00	0.00	24.90	
final base extraction			0.00	0.00	17.40	

2d adsorption equilibrium final waterwash final solvent extraction final base extraction	Solvent Extraction Procedure		Solvent Extraction Procedure		Solvent Extraction Procedure	
	Ci = 1000 uM	C (umol/L)	Q (umol/kg)	Ci = 100 uM	C (umol/L)	Q (umol/kg)
	794.20	NA	284.00	68.88	42.94	6.51
	0.00	0.00	100.30	NA	NA	NA
	0.00	0.00	89.20	0.00	23.40	4.56
				0.00	22.50	0.79

Solvent Extraction Procedure	
Ci = 10 uM	
	5.70
	NA
	0.00
	0.00
	5.94
	NA
	4.32
	3.79

1-Naphthol with Low Organic Soil Anoxic-Biotic Adsorption Conditions

Sorbed Concentration Remaining After:	Waterwash Procedure Ci = 1000 uM		Waterwash Procedure Ci = 100 uM		Waterwash Procedure Ci = 10 uM	
	C (umol/L)	Q (umol/kg)	C (umol/L)	Q (umol/kg)	C (umol/L)	Q (umol/kg)
2d adsorption equilibrium			68.14	43.97		
final waterwash			0.30	14.70		
final solvent extraction			0.00	13.90		
final base extraction			0.00	5.25		
2d adsorption equilibrium final waterwash final solvent extraction final base extraction	Solvent Extraction Procedure Ci = 1000 uM		Solvent Extraction Procedure Ci = 100 uM		Solvent Extraction Procedure Ci = 10 uM	
	Q (umol/kg)	C (umol/L)	Q (umol/kg)	C (umol/L)	Q (umol/kg)	C (umol/L)
2d adsorption equilibrium	752.10	342.10	76.39	32.59	5.93	5.61
final waterwash	NA	NA	NA	NA	NA	NA
final solvent extraction	0.00	65.70	0.00	12.30	0.00	2.83
final base extraction	0.00	65.30	0.00	4.96	0.00	1.38

**1-Naphthol with Low Organic Soil
Oxic-Abiotic Adsorption Conditions**

Sorbed Concentration Remaining After:	Waterwash Procedure Ci = 1000 uM		Waterwash Procedure Ci = 100 uM		Waterwash Procedure Ci = 10 uM	
	C (umol/L)	Q (umol/kg)	C (umol/L)	Q (umol/kg)	C (umol/L)	Q (umol/kg)
2d adsorption equilibrium			75.35	34.06		
final waterwash			0.22	10.58		
final solvent extraction			0.00	7.50		
final base extraction			0.00	6.02		
2d adsorption equilibrium final waterwash final solvent extraction final base extraction	Solvent Extraction Procedure Ci = 1000 uM		Solvent Extraction Procedure Ci = 100 uM		Solvent Extraction Procedure Ci = 10 uM	
		826.70	79.25	28.64	7.59	3.32
	NA	NA	NA	NA	NA	NA
	0.00	33.80	0.00	10.10	0.00	0.78
	0.00	24.40	0.00	7.38	0.00	0.50

**Naphthalene with High Organic Soil
Oxic-Biotic Adsorption Conditions**

Sorbed Concentration Remaining After:	Waterwash Procedure Ci = 100 uM		Waterwash Procedure Ci = 10 uM		Waterwash Procedure Ci = 1 uM	
	C (umol/L)	Q (umol/kg)	C (umol/L)	Q (umol/kg)	C (umol/L)	Q (umol/kg)
2d adsorption equilibrium	6.58	128.92	0.81	12.69	0.08	1.27
final waterwash	0.62	38.56	0.06	4.46	0.01	0.44
final solvent extraction	0.00	1.95	0.00	0.20	0.00	0.03
final base extraction	0.00	1.37	0.00	0.15	0.00	0.03
	Solvent Extraction Procedure Ci = 100 uM		Solvent Extraction Procedure Ci = 10 uM		Solvent Extraction Procedure Ci = 1 uM	
2d adsorption equilibrium	7.68	127.40	0.85	12.63	0.10	1.24
final waterwash	NA	NA	NA	NA	NA	NA
final solvent extraction	0.00	2.26	0.00	0.41	0.00	0.02
final base extraction	0.00	2.22	0.00	0.32	0.00	0.02

Naphthalene with Low Organic Soil Oxic-Biotic Adsorption Conditions

Sorbent Concentration Remaining After:	Waterwash Procedure Ci = 100 uM		Waterwash Procedure Ci = 10 uM		Waterwash Procedure Ci = 1 uM	
	C (umol/L)	Q (umol/kg)	C (umol/L)	Q (umol/kg)	C (umol/L)	Q (umol/kg)
2d adsorption equilibrium	55.12	61.93				
final waterwash	0.08	16.09				
final solvent extraction	0.00	4.90				
final base extraction	0.00	3.40				
Solvent Extraction Procedure Ci = 100 uM						
2d adsorption equilibrium	63.21	50.77	4.23	7.96	0.46	0.75
final waterwash	NA	NA	NA	NA	NA	NA
final solvent extraction	0.00	4.45	0.00	0.66	0.00	0.06
final base extraction	0.00	3.20	0.00	0.57	0.00	0.04
Solvent Extraction Procedure Ci = 10 uM						
2d adsorption equilibrium	63.21	50.77	4.23	7.96	0.46	0.75
final waterwash	NA	NA	NA	NA	NA	NA
final solvent extraction	0.00	4.45	0.00	0.66	0.00	0.06
final base extraction	0.00	3.20	0.00	0.57	0.00	0.04
Solvent Extraction Procedure Ci = 1 uM						
2d adsorption equilibrium	63.21	50.77	4.23	7.96	0.46	0.75
final waterwash	NA	NA	NA	NA	NA	NA
final solvent extraction	0.00	4.45	0.00	0.66	0.00	0.06
final base extraction	0.00	3.20	0.00	0.57	0.00	0.04

APPENDIX IV. BIOAVAILABILITY / ¹⁴CO₂ EVOLUTION RESULTS

**1-Naphthol with High Organic Soil
Oxic-Biotic Adsorption Conditions (C_i = 100 μM)**

Sorption Concentration:	Equilibrium Set		Unwashed Microcosms		Waterwashed Microcosms	
	C (umol/L)	Q (umol/kg)	C (umol/L)	Q (umol/kg)	C (umol/L)	Q (umol/kg)
Initially Present (t = 0d)	6.94	128.42	6.94	128.42	0.07	85.11
After waterwashing	0.07	85.11				
After solvent extraction	0.00	69.40				
After base extraction	0.00	57.10				
After 90d degradation period			BDL	65.40	BDL	55.90
Total 14C Initially Sorbed (DPM)		804605.00		804605.00		538283.00

Unwashed Microcosms	Time (days)	Waterwashed Microcosms	
		Total ¹⁴ CO ₂ evolved (DPM)	Total ¹⁴ CO ₂ evolved (DPM)
	0.00	0.00	
9997.08	1.00	1764.80	
20976.53	4.00	4528.80	
32375.27	7.00	6877.54	
37452.55	14.00	9630.85	
40482.18	21.00	11545.73	
44551.98	28.00	12886.56	
52928.42	35.00	14194.37	
60742.14	42.00	15219.16	
73092.96	49.00	16684.25	
79741.81	56.00	17573.34	
84775.66	63.00	18489.70	
88455.87	70.00	19262.38	
91955.87	77.00	19962.38	
95495.32	83.00	20917.12	
99431.51	90.00	21741.14	

**1-Naphthol with High Organic Soil
Anoxic-Biotic Adsorption Conditions ($C_i = 100 \mu\text{M}$)**

Equilibrium Set		Unwashed Microcosms		Waterwashed Microcosms		
	C ($\mu\text{mol/L}$)	Q ($\mu\text{mol/kg}$)	C ($\mu\text{mol/L}$)	Q ($\mu\text{mol/kg}$)	C ($\mu\text{mol/L}$)	Q ($\mu\text{mol/kg}$)
Sorbed Concentration:						
Initially Present (t = 0d)	10.38	123.68	10.38	123.68	0.09	43.44
After waterwashing	0.09	43.44				
After solvent extraction	0.00	38.40				
After base extraction	0.00	28.70				
After 90d degradation period			BDL	40.90	BDL	37.40
Total 14C Initially Sorbed (DPM)		733837.00		733837.00		257466.00

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Unwashed Microcosms		Waterwashed Microcosms	
Total $^{14}\text{CO}_2$ evolved (DPM)	Time (days)	Total $^{14}\text{CO}_2$ evolved (DPM)	Time (days)
0.00	0.00	0.00	0.00
33101.51	1.00	298.31	
55631.60	4.00	17173.31	
64467.69	7.00	20791.16	
71212.53	14.00	22902.85	
78783.83	21.00	24171.89	
94385.61	28.00	25281.09	
120952.90	35.00	26166.02	
144638.31	42.00	26449.90	
155126.58	49.00	27214.02	
158326.60	56.00	27769.29	
163940.84	63.00	28290.70	
167446.30	70.00	28735.20	
170543.54	77.00	29246.65	
173158.02	83.00	29716.41	
175520.54	90.00	30201.68	

**1-Naphthol with High Organic Soil
Oxic-Abiotic Adsorption Conditions (C_i = 100 uM)**

	Equilibrium Set		Unwashed Microcosms		Waterwashed Microcosms	
	C (umol/L)	Q (umol/kg)	C (umol/L)	Q (umol/kg)	C (umol/L)	Q (umol/kg)
Sorbed Concentration:						
Initially Present (t = 0d)	12.15	121.23	12.15	121.23	0.40	44.72
After waterwashing	0.40	44.72				
After solvent extraction	0.00	38.30				
After base extraction	0.00	33.70				
After 90d degradation period			BDL	43.70	BDL	34.60
Total 14C Initially Sorbed (DPM)		723165.00		723165.00		229718.00
Unwashed Microcosms						
Total 14CO ₂ evolved (DPM)	Time (days)	Waterwashed Microcosms				
0.00	0.00	Total 14CO ₂ evolved (DPM)				
60486.63	1.00	0.00				
72538.02	4.00	3292.44				
81127.32	7.00	19599.52				
99078.39	14.00	25501.01				
118077.52	21.00	33009.42				
129855.12	28.00	34260.83				
135172.30	35.00	36030.23				
138247.38	42.00	37598.27				
140496.44	49.00	39027.42				
143027.01	56.00	40017.81				
144992.07	63.00	41118.56				
146537.93	70.00	42008.15				
148016.00	77.00	42723.23				
149292.29	83.00	43415.34				
150498.91	90.00	44003.31				
		44582.16				

**1-Naphthol with Low Organic Soil
Oxic-Biotic Adsorption Conditions ($C_i = 100 \mu\text{M}$)**

	Equilibrium Set		Unwashed Microcosms		Waterwashed Microcosms	
	C ($\mu\text{mol/L}$)	Q ($\mu\text{mol/kg}$)	C ($\mu\text{mol/L}$)	Q ($\mu\text{mol/kg}$)	C ($\mu\text{mol/L}$)	Q ($\mu\text{mol/kg}$)
Sorbed Concentration:						
Initially Present (t = 0d)	68.88	42.94				
After waterwashing	0.13	26.12			0.13	26.12
After solvent extraction	0.00	24.20				
After base extraction	0.00	20.00				
After 90d degradation period						
Total 14C Initially Sorbed (DPM)		103935.00	BDL	30.00	BDL	18.60
				103935.00		63233.00
Unwashed Microcosms						
Total 14CO ₂ evolved (DPM)						
	0.00					
	49412.05					
	56244.41					
	58353.41					
	67916.90					
	76717.09					
	84992.20					
	90613.90					
	94570.78					
	98114.78					
	101246.71					
	102338.94					
	103069.03					
	103738.38					
	104489.39					
	104951.70					
Waterwashed Microcosms						
Total 14CO ₂ evolved (DPM)						
	0.00					
	463.50					
	811.43					
	1106.66					
	1405.77					
	1644.53					
	1854.29					
	2023.38					
	2247.37					
	2526.24					
	2602.42					
	2689.54					
	2809.96					
	2963.66					
	2982.47					
	3059.65					

**1-Naphthol with Low Organic Soil
Anoxic-Biotic Adsorption Conditions (C_i = 100 uM)**

	Equilibrium Set		Unwashed Microcosms		Waterwashed Microcosms		
	C (umol/L)	Q (umol/kg)	C (umol/L)	Q (umol/kg)	C (umol/L)	Q (umol/kg)	
Sorbed Concentration:							
Initially Present (t = 0d)	72.26	38.28	72.26	38.28	0.30	14.70	
After waterwashing	0.30	14.70					
After solvent extraction	0.00	13.09					
After base extraction	0.00	5.11					
After 90d degradation period							
Total 14C Initially Sorbed (DPM)		94250.00	BDL	21.60	BDL	12.90	
				94250.00		52072.00	
Unwashed Microcosms	Waterwashed Microcosms						
Total 14CO ₂ evolved (DPM)	Time (days)	Total 14CO ₂ evolved (DPM)					
0.00	0.00	0.00					
38193.76	1.00	83.40					
45193.83	4.00	263.20					
47641.78	7.00	429.09					
49104.04	14.00	634.60					
53616.03	21.00	765.74					
57161.21	28.00	912.96					
59382.07	35.00	1050.36					
63006.09	42.00	1279.52					
66644.61	49.00	1355.91					
70297.58	56.00	1481.56					
73079.70	63.00	1544.38					
74507.40	70.00	1547.20					
75395.01	77.00	1684.61					
75853.40	83.00	1822.01					
76311.81	90.00	1959.42					

**1-Naphthol with Low Organic Soil
Oxic-Abiotic Adsorption Conditions ($C_i = 100 \mu M$)**

		Equilibrium Set		Unwashed Microcosms		Waterwashed Microcosms	
Sorbed Concentration:		C (umol/L)	Q (umol/kg)	C (umol/L)	Q (umol/kg)	C (umol/L)	Q (umol/kg)
Initially Present (t = 0d)		77.28	31.35	77.28	31.35	0.22	10.58
After waterwashing		0.22	10.58				
After solvent extraction		0.00	8.80				
After base extraction		0.00	6.70				
After 90d degradation period				BDL	15.60	BDL	5.00
Total 14C Initially Sorbed (DPM)			109509.00		109509.00		42897.00
		Unwashed Microcosms		Waterwashed Microcosms			
Total 14CO ₂ evolved (DPM)		Time (days)	Total 14CO ₂ evolved (DPM)	Time (days)	Total 14CO ₂ evolved (DPM)		
0.00		0.00	0.00				
43965.44		1.00	54.63				
55598.91		4.00	186.20				
57522.50		7.00	258.62				
58251.89		14.00	306.19				
61726.96		21.00	348.76				
64572.40		28.00	436.86				
67074.17		35.00	536.62				
70320.52		42.00	647.92				
73070.04		49.00	716.41				
75819.57		56.00	777.91				
77556.32		63.00	817.06				
81069.47		70.00	862.61				
81939.83		77.00	934.50				
82507.97		83.00	1006.38				
82792.87		90.00	1078.27				

**Naphthalene with High Organic Soil
Oxic-Biotic Adsorption Conditions (C_i = 100 µM)**

Equilibrium Set	Unwashed Microcosms		Waterwashed Microcosms	
	C (µmol/L)	Q (µmol/kg)	C (µmol/L)	Q (µmol/kg)
Sorbed Concentration:				
Initially Present (t = 0d)	7.18	128.09	7.18	128.09
After waterwashing	0.62	38.56	0.62	38.56
After solvent extraction	0.00	2.10	0.00	2.10
After base extraction	0.00	1.80	0.00	1.80
After 90d degradation period				
Total 14C Initially Sorbed (DPM)		473952.00	BDL	13.10
			BDL	4.60
				142815.00

Unwashed Microcosms	Waterwashed Microcosms	
	Time (days)	Total 14CO ₂ evolved (DPM)
Total 14CO ₂ evolved (DPM)	0.00	0.00
	67.62	9616.46
	15002.75	24145.01
	42346.84	34120.15
	49979.17	39058.69
	53245.60	42637.21
	55512.25	44467.63
	57315.82	45714.84
	58559.20	46598.96
	62582.83	47176.01
	66547.28	47682.50
	70195.66	48182.50
	73095.66	49092.66
	75995.66	49325.17
	78943.21	49592.23
	81472.31	49808.90

Naphthalene with Low Organic Soil Oxic-Biotic Adsorption Conditions ($C_i = 100 \text{ uM}$)

Sorbed Concentration:	Equilibrium Set			Unwashed Microcosms		Waterwashed Microcosms	
	C (umol/L)	Q (umol/kg)		C (umol/L)	Q (umol/kg)	C (umol/L)	Q (umol/kg)
Initially Present ($t = 0\text{d}$)	59.17	56.35		59.17	56.35	0.08	16.09
After waterwashing	0.08	16.09					
After solvent extraction	0.00	4.80					
After base extraction	0.00	3.30					
After 90d degradation period				BDL	7.60	BDL	2.50
Total 14C Initially Sorbed (DPM)		305020.00			305020.00		91180.00

Unwashed Microcosms	Waterwashed Microcosms	
	Time (days)	Total 14CO ₂ evolved (DPM)
Total 14CO ₂ evolved (DPM)	0.00	0.00

169426.00	1.00	158.91
177234.29	4.00	2147.33
179758.18	7.00	2723.45
180930.97	14.00	3945.96
185384.61	21.00	4200.48
191012.97	28.00	4467.29
194433.38	35.00	4714.36
198220.14	42.00	4961.44
201420.14	49.00	5206.78
204035.34	56.00	5351.50
205719.58	63.00	5461.40
207147.13	70.00	5528.25
207891.21	77.00	5652.84
208534.53	83.00	5777.44
211390.59	90.00	5902.04

APPENDIX V. THIN LAYER CHROMATOGRAPHY RESULTS

1-Naphthol with High Organic Soil Oxic-Biotic Adsorption Conditions

Initial Aqueous Concentration	Aqueous Supernatant		Solvent Extract	
	Rf value	% 14C Activity	Rf value	% 14C Activity
1000 uM	0.74	98.70	0.74	97.60
	0.26	0.07	0.60	2.40
			(0.58-0.65)	
	0.74	97.60		
	0.26	1.30		
100 uM	0.72	88.70	0.72	92.40
	0.28	5.30	0.60	3.80
			(0.57-0.65)	
	0.72	90.70		
	0.27	7.90		
10 uM	0.72	51.50	0.72	88.50
	0.28	36.50	0.60	7.70
			(0.58-0.64)	

**1-Naphthol with High Organic Soil
Anoxic-Biotic Adsorption Conditions**

Initial Aqueous Concentration	Aqueous Supernatant		Solvent Extract	
	Rf value	% 14C Activity	Rf value	% 14C Activity
1000 uM	0.72	97.20	0.72	94.10
	0.58	2.40	0.47	0.80
	0.28	0.03		
100 uM	0.70	89.10	0.70	91.40
	0.57	5.70	0.46	1.30
	0.26	1.00		
10 uM	0.73	85.50	0.69	88.50
	0.61	4.70	0.44	2.00
	0.22	0.70		

**1-Naphthol with High Organic Soil
Oxic-Abiotic Adsorption Conditions**

Initial Aqueous Concentration	Aqueous Supernatant		Solvent Extract	
	Rf value	% 14C Activity	Rf value	% 14C Activity
1000 uM	0.71	99.10	0.71	95.30
	0.36	0.20	0.38	0.60
	0.73	97.80		
	0.62	0.50		
	0.25	0.30		
100 uM	0.73	95.30	0.71	95.90
	0.62	1.60	0.59	0.40
	0.28	0.60	0.29	0.30
	0.73	94.90		
	0.62	1.00		
	0.28	0.40		
10 uM	0.74	87.70	0.71	94.50
	0.62	5.30	0.40	0.80
	0.33	1.30		
	0.73	92.50		
	0.62	1.60		
	0.27	1.20		

**1-Naphthol with Low Organic Soil
Oxic-Biotic Adsorption Conditions**

Initial Aqueous Concentration	Aqueous Supernatant		Solvent Extract	
	Rf value	% 14C Activity	Rf value	% 14C Activity
1000 uM	0.73	97.00	0.72	92.50
	0.60	0.30	0.46 (0.38-0.54)	1.20
100 uM	0.71	90.30	0.73	92.90
10 uM	0.72	93.80	0.73	91.70
			0.44 (0.32-0.54)	2.90

**1-Naphthol with Low Organic Soil
Anoxic-Biotic Adsorption Conditions**

Initial Aqueous Concentration	Aqueous Supernatant		Solvent Extract	
	Rf value	% 14C Activity	Rf value	% 14C Activity
1000 uM	0.73	97.00	0.72	94.70
	0.60	0.30	0.60	2.50
100 uM	0.73	96.00	0.73	92.90
	0.59	0.80		
10 uM	0.71	95.80	0.73	78.90

**1-Naphthol with Low Organic Soil
Oxic-Abiotic Adsorption Conditions**

Initial Aqueous Concentration	Aqueous Supernatant		Solvent Extract	
	Rf value	% 14C Activity	Rf value	% 14C Activity
1000 uM	0.73	98.70	0.73	93.90
	0.63	0.30	0.56	2.20
			(0.46-0.67)	
100 uM	0.73	97.50	0.73	91.00
	0.61	0.50	0.25	0.80
10 uM	0.73	96.10	0.73	83.60
	0.62	1.10	0.27	1.20

**Naphthalene with High Organic Soil
Oxic-Biotic Adsorption Conditions**

Initial Aqueous Concentration	Aqueous Supernatant		Solvent Extract	
	Rf value	% 14C Activity	Rf value	% 14C Activity
100 uM 2d Contact Time	0.81	95.10	0.80	98.40
	0.39	4.90	0.58	1.60
100 uM 10d Contact Time	0.80	100.00	0.80	99.50
			0.61	0.50
100 uM 30d Contact Time	0.81	93.30	0.81	99.00
	0.60	6.70	0.61 (0.57-0.68)	1.00
100 uM 200d Contact Time	0.81	97.30	0.80	97.60
	0.61	2.70	0.70	1.80
	(.55 - .65)		0.61	0.60
10 uM	0.80	98.90	0.80	97.30
	0.39	1.10	0.61	2.70
			(0.56-0.66)	
	0.72	90.70		
	0.27	7.90		
1 uM	0.80	95.40	0.80	100.00
	0.39	2.30		

**Naphthalene with Low Organic Soil
Oxic-Biotic Adsorption Conditions**

Initial Aqueous Concentration	Aqueous Supernatant		Solvent Extract	
	Rf value	% 14C Activity	Rf value	% 14C Activity
100 uM	0.81	94.60	0.81	99.00
	0.70	3.80	0.42	1.00
			(0.35-0.48)	
10 uM	0.80	100.00	0.80	97.40
			0.42	2.60
			(0.39-0.50)	
1 uM	0.80	100.00	0.80	100.00

VITA

William David Burgos was born January 26, 1966 in Trenton, NJ. He grew up in Yardley, PA and for a few years in Clifton Park, NY. He attended public schools in both of these communities, graduating from Pennsbury High School in June 1984. In September 1984 he enrolled at Virginia Polytechnic Institute & State University (Virginia Tech), Blacksburg, VA. During his undergraduate years he worked for General Electric Astro Space Division in Princeton, NJ. He completed a B.S. in Mechanical Engineering in May 1989 and then a M.S. in Environmental Engineering in December, 1990, both from Virginia Tech. His master thesis research focused on sludge dewatering. Between January 1991 and August 1992 he worked for the environmental consulting firms Geraghty & Miller in Newtown, PA and EnviroTech Mid-Atlantic in Blacksburg, VA. In August 1992 he enrolled in the Environmental Engineering Ph.D. program at Virginia Tech and completed this final degree in May 1995. Mr. Burgos will join the faculty of the Department of Civil and Environmental Engineering at The Pennsylvania State University starting in August 1995.

A handwritten signature in black ink that reads "William D. Burgos". The signature is written in a cursive style with a large, prominent initial 'W' and a long, sweeping underline.