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Dissipation of polycyclic aromatic hydrocarbons (PAHs) in the rhizosphere: Synthesis through meta-analysis

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The meta-analysis provides the first quantitative evidence of the positive effect of rhizosphere processes on PAH dissipation.

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ABSTRACT

Polycyclic aromatic hydrocarbons (PAHs) are widespread and persistent organic pollutants with high carcinogenic effect and toxicity; their behavior and fate in the soil–plant system have been widely investigated. In the present paper, meta-analysis was used to explore the interaction between plant growth and dissipation of PAHs in soil based on the large body of published literature. Plants have a promoting effect on PAH dissipation in soils. There was no difference in PAH dissipation between soils contaminated with single and mixed PAHs. However, plants had a more obvious effect on PAH dissipation in freshly-spiked soils than in long-term field-polluted soils. Additionally, a positive effect of the number of microbial populations capable of degrading PAHs was observed in the rhizosphere compared with the bulk soil. Our meta-analysis established the importance of the rhizosphere effect on PAH dissipation in variety of the soil–plant systems.

1. Introduction

Although polycyclic aromatic hydrocarbons (PAHs) can be found in soil naturally, their presence, particularly in high concentration, is commonly associated with anthropogenic inputs (Harvey, 1991; Hwang and Cutright, 2006). Although there are a huge number of PAH compounds, only 16 species are currently included in the Priority Pollutants List of the U.S. Environmental Protection Agency (USEPA) based on their environmental abundance and toxicity (Keith and Telliard, 1979). The presence of PAHs in contaminated soil may pose risks to human health and the environment due to their toxicity (Zmirou et al., 2000; Huang et al., 2004).

The elimination of PAHs from contaminated soil is based on various remediation approaches geared toward relevant cleanup standards. The available technologies for the removal of PAHs includes thermal decomposition (e.g. incineration), physicochemical treatment (e.g. extraction and treatment with specific chemicals) (Bonten et al., 1999; Tang, 2004), and bioremediation (e.g. decomposition by indigenous and exogenous microorganisms and plants) (Salanitro et al., 1997; Dorn and Salanitro, 2000; Chaineau et al., 2003). Out of the three options mentioned above, bioremediation of PAHs is a low-cost technology of low-cost that can achieve complete PAH degradation with little soil disturbance (Habe and Omori, 2003; Mackova et al., 2006).

Given a wide range of catabolic reactions mediated by microbial enzymes, it is not surprising that initial PAH bioremediation research focused on the biodegradation by microorganisms (Mackova et al., 2006). A large number of microbial populations capable of degrading PAHs were isolated from the contaminated soils, and many PAH-catabolizing genes from either fungi or bacteria were identified (e.g. Peng et al., 2008). In rhizosphere, where plant roots interact with soil as well as microbes, the activities and abundance of microbes were significantly enhanced. For this reason, the contribution that plants can make to the successful remediation must not be ignored (Huang et al., 2004; Mackova et al., 2006; Olson et al., 2008; He et al., 2009).

Plants promote PAH dissipation by three strategies: immobilization, removal and promotion of microbial degradation. PAH immobilization occurs on the soil organic matter (that plants contribute to) and the mineral phase, creating a non-extractable PAH fraction (Luthy et al., 1997; Northcott and Jones, 2001) with low bioavailability (White et al., 1997; Reid et al., 2000; Semple et al., 2003) and mobility in the environment. Plants can remove PAHs via uptake by roots and translocation to the aboveground

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plant parts. In terms of PAH degradation, plants do possess enzymes that can break down some PAHs as shown in cultures of non-photosynthetic tissues and axenic roots; however, it is soil microflora in the rhizosphere that is vitally important in degradation of xenobiotics, including PAHs (Mackova et al., 2006). Both the microbial biomass and the number of PAH decomposers were greater in the rhizosphere of ryegrass and clover than in the bulk soil (Johnson et al., 2005; Olson et al., 2008). Hence, contribution of plants to PAH dissipation by immobilization, removal and degradation is strongly dependent on the rhizosphere processes.

The effect of PAHs on plant growth is concentration-dependent. Exposure to low doses of PAHs increased plant weight, a phenomenon termed 'hormesis', as a general aspect of environmental stress (Laughlin et al., 1981; Calabrese, 2004; Belz et al., 2008; Calabrese and Blain, 2009). In contrast, high doses of PAHs hamper and eventually inhibit plant growth. PAHs can penetrate through the cell membranes (Chaineau et al., 1997), decrease water and nutrient utilization efficiency (Reilley et al., 1996; Salanitro et al., 1997), and inhibit photosynthetic activity and electron transport (Mallakin et al., 2002). Different plant species respond differently to the presence of PAHs in soil. For example, in the same PAH treatment, biomass of *Panicum bisulcatum* was reduced by approximately 70%, whereas biomass of *Aeschynomene indica* was higher in PAH-treated than the control soil (Lee et al., 2008). There are other reports showing no effect of PAHs on plant biomass (Xu et al., 2006; Chiapusio et al., 2007), which might be dependent on the experimental conditions.

The plant potential to influence the remediation of PAH compounds has led to many studies of the rhizosphere effects on PAH dissipation (Kamath et al., 2005; Parrish et al., 2005; Mueller and Shann, 2007; Su and Zhu, 2008). However, plant species vary widely in their efficiency of PAH dissipation. In addition, there are also differences among genotypes within a species. Many reviews on phytoremediation have focused on summarizing the observed variable responses from numerous studies involving a wide range of plant species, PAH types and concentrations, and experimental conditions; however, a synthetic analysis of the reasons underlying differential PAH dissipation in the soil–plant system is lacking.

In the present paper, meta-analytic techniques, which combine the results of many studies that address a set of related research hypotheses, were used to reveal the effect of plants on PAH dissipation. For each hypothesis, we tested the effects of rhizosphere on PAH dissipation, the number of PAH-decomposing microorganisms in the rhizosphere, and the effect of PAHs on plant growth. It is hypothesized that plants can promote PAH dissipation and the number of PAH decomposers, whereas PAHs can negatively influence plant growth. Furthermore, we hypothesized that the PAH effect would be large (1) in freshly-spiked soils compared to aged field-contaminated soils, (2) in soils contaminated with mixed PAHs compared to soils contaminated with a single PAH compound, (3) for the low-molecular-weight compared to high-molecular-weight PAHs, and (4) for species with a large root system compared to those with a small one.

2. Materials and methods

2.1. Effect sizes

The primary goal was to achieve an overall characterisation, including magnitude and direction (positive or negative) of the plant effect on dissipation of PAHs and microbial decomposers in the rhizosphere, as well as of the influence of PAHs on plant growth. We searched Web of Knowledge and BIOSIS for the primary literature on the rhizosphere effects on dissipation of PAHs in soil using all combinations of terms: *polycyclic aromatic hydrocarbons* or *PAHs* or the names of all 16 PAHs in the EPA priority pollutants list combined with the terms 'rhizosphere' and 'soil'. The first criterion was that the studies should include the mean PAH concentrations for both an experimental group (rhizosphere or planted treatment) and an appropriate control group (bulk soil or unplanted treatment), with an error (or other statistical parameters) and sample size for both the experimental group and control. Further details on this criterion are available in the Supplementary material. In total, 141 articles were identified; however, only 41 had the primary data on dissipation of PAHs in the rhizosphere that met our criteria, generating the total of 668 comparisons of 51 species and 1 (simulated) anthropogenic root exudate (ARE). Hedges' *d*, which is an unbiased weighted measure of the differences between the means of control and experimental groups divided by the pooled standard deviation and multiplied by a correction term to adjust for small sample size, was selected as the metric of the standardized effect size (Hedges and Olkin, 1985). Bulk and rhizosphere soils, or unplanted and planted soils (when soils were not defined as "bulk" and "rhizosphere"), were defined as a control group and an experimental group, respectively. For specific factors, negative value of *d* indicates (i) enhancement of PAH dissipation, (ii) a decreased number of microbial decomposers, and/or (iii) decreased plant growth; positive *d* has the opposite meanings. JMP 7.0 (SAS Institute Inc.) was used for all statistical procedures.

2.2. Models

For full models that used all the effect sizes in one analysis, the output of each statistical test consisted of the grand mean effect size for analysis with an accompanying bias-corrected bootstrapped 95% confidence interval (*CI*) and a total heterogeneity statistic (*Q*). The random-effects model, instead of fixed-effects model, was employed to calculate the grand mean effect size for each analysis because the true effect size varied among studies due to the broad range of plant taxa used in these studies (Gurevitch and Hedges, 1999). The mean effect size is significantly different from zero when the confidence intervals do not overlap with zero (Adams et al., 1997). The heterogeneity statistic is a weighted sum of squares and is tested against Chi-square distribution with n-1 degrees of freedom. A significant value of *Q* in a random-effects model indicates that the variation among effects is greater than expected from the sampling error, real variation in effect sizes (random component of model) and group differences, suggesting that all effect sizes may not have come from the same population (Rosenberg et al., 2000).

In order to examine the similarity in the effect size among different groups (including PAH sources and experimental conditions), the heterogeneity of mean effect sizes between groups was tested separately by exploratory analyses using mixed-effects models. A mean effect size and a bias-corrected bootstrapped 95% confidence interval were calculated for each group in the exploratory analyses. Heterogeneity statistics were calculated to quantify both within-group (Q_W) and between-group (Q_B) variation. The interpretation of significant values of *Q* in the mixed-effects models is similar to that in the random-effects models, in which significant values of *Q* suggest that observed variation is greater than expected due to the sampling error, real variation in effect sizes and group differences (Gurevitch and Hedges, 1999). The mean effect sizes between studies conducted with freshly-spiked soils and aged contaminated soils as well as between soils with single and mixed PAHs were compared.

2.3. Source of heterogeneity within-group

It is assumed that variation in the effect size could be due to taxonomic grouping, dose rate, PAH type, and treatment period in each experiment. The PAH sources and taxonomic information for plants were used to identify source of heterogeneity within the group (Q_w). A mixed-effects model was used to compare the mean effect sizes between different taxonomic groups and PAHs. However, when the purpose was not to explain or partition the effects in the literature, but rather to quantify underlying patterns, the mixed-effects model is not ideal and may even be problematic in most cases. As a result, the continuous random-effects model was used to explore the relationship between the effect size and the period of culture and aging, dose of PAHs, and soil properties when available. The methods and results of sensitivity analysis and publication bias were presented in the Supplementary material.

3. Results

3.1. Effect of plants on PAH dissipation

Plants had a significant promotional influence on the dissipation of PAHs, representing a negative effect size in the full model (Fig. 1). There was a non-significant difference in the effect sizes between soils with mixed and single PAHs, but a significant difference ($p < 0.0001$) between freshly-spiked and aged field-contaminated soils. By convention, a value of *d* greater than or equal to 0.8 is a large effect, *d* equal to 0.5 is a moderate effect and *d* equal to 0.2 is a small effect (Gurevitch et al., 1992). Based on these criteria, plants had a large effect on PAH dissipation in all groups (all the effect size estimates were significantly different from zero), especially in the

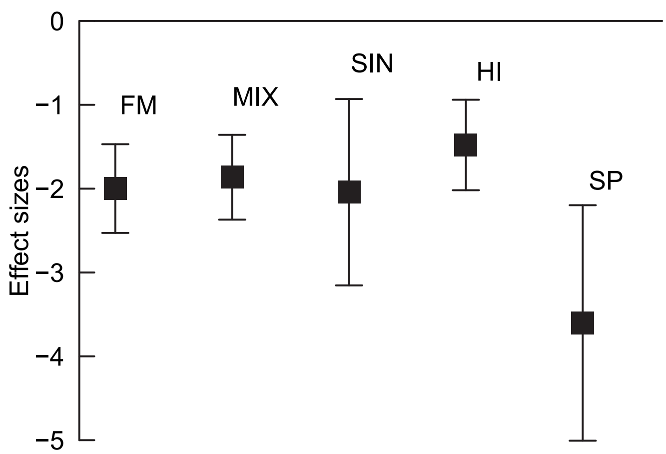

Fig. 1. Plant effect on PAH dissipation. The mean and the 95% confidence interval (vertical bars) are shown for each analysis. No confidence interval overlaps zero; hence, all means are significantly different from zero. FM, full model; MIX, soils with mixed PAHs; SIN, soils with single PAHs; HI, field-contaminated soils; SP, spiked soils.

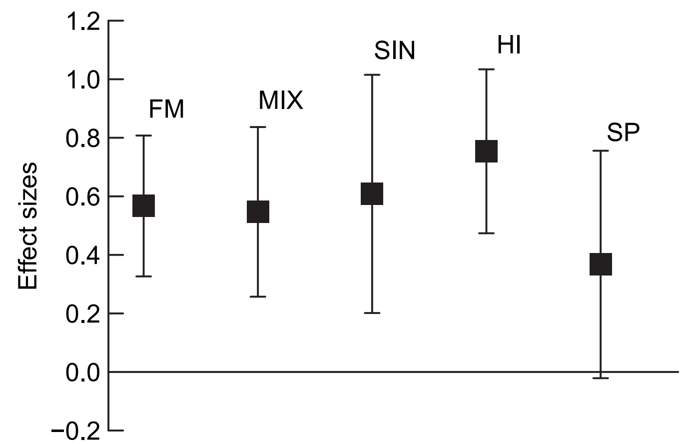

Fig. 2. Plant effect on the number of PAH decomposers. The mean and the 95% confidence interval (vertical bars) are shown for each analysis. No confidence interval overlaps zero; hence, all means are significantly different from zero. FM, full model; MIX, soils with mixed PAHs; SIN, soils with single PAHs; HI, field-contaminated soils; SP, spiked soils.

freshly-spiked soils, in which case plants had an effect size larger than 3 on the dissipation of PAHs.

In all models of PAH dissipation, significant within-group heterogeneity was observed (Table 1). In an attempt to characterize that heterogeneity, PAHs source and taxonomic groups were chosen for classification. There were significant differences in the mean effect size between different PAHs (Table S1). With the exception of anthracene, fluorene, pyrene, and benzo[k]-fluoranthrene, mean effect sizes of all other PAHs were significantly different from zero. Plants had the greatest effect size ($d+ = -7.9$) on dissipation of acenaphthylene, and had effect sizes ranging on most other PAH compounds. The mean effect sizes varied significantly among different plant families (Table S2). With the exception of Lamiaceae, there were negative effects in all groups. The effect sizes in Polygonaceae and Verbenaceae were, however, not significantly different from zero. Moreover, significant within-group heterogeneity was observed in all models of PAH dissipation. Further partitioning of variability was, however, limited by the number of comparisons within groups. The relationship between the effect sizes and variables was significant in models of soil cation exchange capacity (CEC), organic carbon, time of plant growth, and dose of mixed PAHs, and marginally significant in the model of time of aging (Table S3). However, non-significant residual error was observed in each model.

3.2. Effect of plants on microbial populations capable of decomposing PAHs

Plants had a positive effect on the number of cultivable PAH degraders in soils (based on the most probable number (MPN)) (Fig. 2). However, no significant differences in the number of cultivable PAH decomposers were detected between soils with single and mixed PAHs, nor between freshly-spiked and aged field-contaminated soils. Plants had a moderate effect on the number of PAH decomposers in the full model ($d+ = 0.53$), soils with mixed PAHs ($d+ = 0.55$), and long-term field-contaminated soils ($d+ = 0.70$). The effect sizes were small in soils with single PAH contamination ($d+ = 0.45$) and freshly-spiked soils ($d+ = 0.31$). All the effect size estimates were significantly different from zero, except the effect size of freshly-spiked soils.

In all models, within-group heterogeneity statistics were non-significant (Table 2), which indicated that variation is entirely due to a sampling error, a random component of the model, and group difference. Therefore, further analysis was not done.

3.3. Effect of PAHs on plant growth

Growth of roots and shoots was inhibited by PAHs in freshly-spiked soils (Fig. 3). PAHs had a moderate negative effect size on growth of roots ($d+ = -0.75$) and shoots ($d+ = -0.57$) in soils contaminated with mixed PAHs, whereas small negative effects were found in soils contaminated with single PAHs ($d+ = -0.27$ and -0.31 for roots and shoots, respectively). There were significant differences in root growth ($p = 0.009$), but only marginally significant differences in shoot growth ($p = 0.08$) between soils contaminated with mixed and single PAHs. Similarly to other analyses, the mean effect sizes for each group were significantly different from zero, except for root and shoot biomass in the freshly-spiked soils.

Within-group heterogeneity statistics were significant in most cases in root and shoot growth models (Table 3). Taxonomic

Table 1
Total heterogeneity statistic (Q) for each model in the analysis of PAH dissipation.

Statistical model	Free degree	Q	Probability
Full model	668	1874.5	0
Spiked and aged			
Between-group	1	8.4	0.004
Within-group	667	1789.8	0
Single and mixed			
Between-group	1	2.7	0.1
Within-group	667	1865.2	0

Table 2
Total heterogeneity statistic (Q) for each model in the analysis of the most probable number (MPN) of PAH decomposers.

Statistical model	Free degree	Q	Probability
Full model	86	99.4	0.15
Spiked and aged			
Between-group	1	2.6	0.11
Within-group	85	91.9	0.29
Single and mixed			
Between-group	1	0.2	0.62
Within-group	85	97.9	0.16

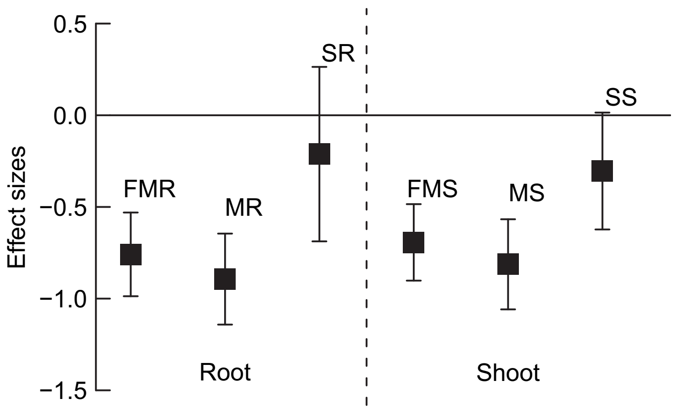

Fig. 3. The effect of PAHs on plant growth. The mean and the 95% confidence interval (vertical bars) are shown for each analysis. No confidence interval overlaps zero; hence, all means are significantly different from zero. FMR, full model of root growth; FMS, full model of shoot growth; MS, shoot growth in soils with mixed PAHs; SS, shoot growth in soils with single PAHs; MR, root growth in soils with mixed PAHs; SR, root growth in soils with single PAH.

grouping rather than PAHs source was used to identify the heterogeneity because most tested soils were spiked with more than one PAH compound. There were significant differences among different plant families in shoot and root growth analyses (Table S4). Regardless of the small sample sizes, the 95% CI varied over a wide range. Correlation analyses showed that the shoot growth was significantly correlated with the aging time and concentrations of individual PAHs, whereas the root growth was significantly correlated with the culture period (days after planting) and concentrations of single and mixed PAHs (Table S5). With the exception of concentration of single PAHs, all other residual errors were significant in each model for shoot and root growth testing the dose, the duration of the culture period and the aging time.

4. Discussion

In our analyses, plants had a large negative effect sizes on PAH dissipation in soils. Traditional literature reviews of the plant effects on PAH dissipation generally suggested wide variation among species and genotypes (Harvey et al., 2002; Singh, 2003; Chaudhry et al., 2005; Pilon-Smits, 2005; Doty, 2008). A ‘vote-count’ of all comparisons included in the meta-analyses would produce an unclear result because approximately only a half of the comparisons recorded a significant plant-promoting effect on PAH dissipation, although 72% of studies reported lower concentrations of PAHs in the rhizosphere than in the bulk soils. In contrast, meta-analysis has the potential to identify broad trends that otherwise may be obscured by intra-experimental variation and the poor statistical power. Both the size of the measured effect and the sample size of each treatment can influence the significance of the results (Gurevitch et al., 1992). Such influence may lead to different statistical outcomes for two studies measuring the same effect simply due to different sample sizes.

Because of the high values of heterogeneity statistics in analyses of either PAH dissipation or PAH effects on plant growth, the grand mean effect plus the 95% CI may not be an accurate estimate of the true distribution of plant effects on PAH dissipation and PAH effects on plant growth (cf. Hedges and Olkin, 1985; Gurevitch et al., 1992). However, after removing the largest effect sizes, the heterogeneity statistic became non-significant. Thus, it is possible that there were some distinct effect size populations that could not be isolated using taxonomic or PAH groupings.

To explore the heterogeneity further, the details of each comparison with the largest effect sizes were examined to find out commonalities that may indicate the source of the large effect sizes. In the PAH dissipation analyses, the large effect sizes were almost equally distributed across the freshly-spiked and aged fiel-contaminated soil groups. Only 42 of 315 excluded effect sizes were single PAH experiments (but note that only 81 comparisons among the total of 668 used single PAH contamination). The excluded largest effect sizes tended to be evenly distributed in most plant families. The largest negative effect sizes resulted from the analyses of naphthalene, phenanthrene, anthracene, pyrene, and chrysene, which may have been linked to greater numbers of comparisons for these 5 than for other PAHs. Because all comparisons in the plant growth analyses were based on spiked experiments, the PAHs source and plant species varied over a relatively narrow range.

Considering a general lack of commonality between comparisons with the largest effect sizes in PAH dissipation, the potential reasons for the heterogeneity cannot be determined. However, removing comparisons with the largest effect sizes from the analysis is unreasonable. Therefore, the following discussion was based on the full analysis, cautiously interpreting results that were altered by the removal of the large effect sizes. It was suggested that for the majority of the comparisons in these analyses, the estimate of mean effect size and the associated 95% CI is a reasonable approximation of the effect of rhizosphere on PAH dissipation, and the effect of PAHs on the number of decomposers and the plant growth. Furthermore, it is important to realize that the large significant heterogeneity observed in these models was driven by extremely large negative effect sizes, which were outside the expected distribution of effect sizes. These large effect sizes might have been due to extreme experimental conditions. More research into organisms with large effect sizes is necessary to explore the bias toward the large effect size. Surprisingly, the effect sizes of all models were consistent either with or without inclusion of these extremely large effect size estimates.

The effect sizes of PAH dissipation and plant growth vary among different species as well as PAH sources, but the general effect tends to be negative despite different plant taxonomic groups, PAH species, and sources of contamination. In contrast, the effect sizes of ‘the rhizosphere effect’ on the amount of decomposers tend to be persistently positive. Published studies highlight the variable distribution of effect sizes as represented by mean and 95% CIs. The effect sizes in these analyses ranged from −4.5 to 6.6. Although the overall effect size was small and negative, various taxonomic groups as well as individual plant species might vary widely in their effects. The root parameters, e.g. morphology, root exudation, root diameter, proportion of fine roots, and associated microbial communities are known to vary widely among plant species (Marschner et al., 2006, 2007; Zhang et al., 2007a, 2007b). It would be expected that remediation potential would vary across plant

Table 3
Total heterogeneity statistic (Q) for the full model in the plant growth analysis. The subgroups for root and shoot growth were based on the condition of spiking soil with single or mixed PAHs.

Statistical model	Free degree	Q	Probability
Root			
Full model	159	257.9	0
Between-group	1	6.9	0.009
Within-group	158	249.0	0
Shoot			
Full model	159	235.1	0.0001
Between-group	1	3.1	0.08
Within-group	158	232.3	0.0001

species because PAH dissipation in the planted soil is associated closely with the rhizosphere effect. Olson et al. (2007) demonstrated that the family Poaceae (grasses) was the most effective among eight families tested, and several studies showed that grasses were more effective than Fabaceae (Gao et al., 2006; Chiapusio et al., 2007; Lee et al., 2008). However, the most effective families in our analysis were Alliaceae ($d+ = -6.83$) and Chenopodiaceae ($d+ = -6.12$), with species of aromatic plants from these families tested in the studies we included in our meta-analysis. May be it is predominance of aromatic plants in phytoremediation because of their potential in releasing aromatic compounds into the rhizosphere, which would enhance the capacity of microbes to utilize PAHs. However, further studies (especially with tree species) are necessary to confirm the efficiency ranking of various families and species. Moreover, significant heterogeneity in the effect sizes for plant taxonomic groups reflects intra- and inter-species variation in addition to variation due to PAH types and experimental conditions, such as period of aging, planting, and dose rate.

The bioavailability of different PAHs in soil varies greatly. In our analyses, significant differences in PAHs dissipation in rhizosphere were observed among PAH types. The mean effect sizes of acenaphthylene, anthracene, fluorene, pyrene, and benzo[k]fluornathrene were smaller than for the others and not significantly different from zero. The highest effect size among all the PAHs investigated was found for naphthalene which had the highest bioavailability and the least number of aromatic rings. Most studies focused on the PAHs with low-molecular-weight, e.g. naphthalene, phenanthrene, and anthracene because degradation of these PAHs was easier than that of fused PAHs with five rings or more. Indeed, little is known about the bacteria capable of utilizing PAHs that contain five or more rings as an energy source. However, diverse fungi revealed the capabilities of biodegrading both low-molecular-weight and high-molecular-weight PAHs, e.g. benzo[a]pyrene, chrysene, benzo[b]fluoranthene, benzo[k]fluoranthene, and benzo[ghi]perylene (Peng et al., 2008). As a result, phytoremediation, or rhizoremediation, was proposed to be efficient because the rhizosphere effects enhanced microbial activities (Pilon-Smits, 2005; Campos et al., 2008). Higher soil organic matter content in soil could increase sequestration of PAHs, thus decreasing the concentration of extractable PAHs, and was therefore considered a dissipation strategy (Chen et al., 2003; Jouanneau et al., 2005; Kamath et al., 2005). Although not all the differences were significant from zero [wide CI in the analysis was likely due to the small sample size ($n < 5$) in most studies], our results demonstrated that the promoting effects on PAH dissipation in the rhizosphere were wide-spread, even for six-ring PAHs.

There were significant differences in PAH dissipation and the numbers of decomposers between freshly-spiked and aged field-contaminated soils, suggesting that the magnitude of the effect sizes can be predicted by the source of pollutants, but also to some extent because of the significant heterogeneity in PAH dissipation. The bioavailability of PAHs in freshly-spiked soils was expected to be greater than that in aged field-contaminated soils. Aging effect of organic compounds, caused by both degradation and sequestration (Northcott and Jones, 2001), may be the key mechanism accounting for the difference in PAH bioavailability between the freshly-spiked and the aged field-contaminated soils. The aging period for spiked soils in all comparisons included in our analysis ranged from one day to six months, whereas the field-contaminated soils had been contaminated for years. According to the results of Northcott and Jones (2001), the half-lives for the apparent loss of PAHs by sequestration depended on compound characteristics and could vary from 96 to 1789 day. Although it is obviously cursory to determine an adequate aging period, it is clear that the aging period for spiked soils was generally much shorter than calculated half-lives. It is assumed that the proportion of sequestered PAHs is greater in aged field-contaminated soils than in freshly-spiked soils, whereas the bioavailability of PAHs could be higher in spiked soils because of the shorter aging period. As a result, the effect sizes of PAH dissipation in field-contaminated soils were smaller than those in spiked soils. The significant heterogeneity indicated more than one population of effects in our analysis.

It is well-known that microbes are abundant in the rhizosphere compared with the bulk soil because of the root activities, or 'the rhizosphere effect'. The number of PAH decomposers is, however, influenced by root exudates in two opposing ways. On one hand, the root exudates promoted the activity of microbes, including the decomposers in the rhizosphere (He et al., 2005, 2007; Mackova et al., 2006; Cofield et al., 2008; Lee et al., 2008; Ding et al., 2009). On the other hand, root exudates may facilitate flourishing of microbes that may compete with, and thus inhibit, PAH decomposers (Jones et al., 2004; Rentz et al., 2004, 2005). The positive effect sizes in our analysis suggested that the PAH decomposers in soil are more likely to be enhanced by root activities than to be inhibited by other microbes in the rhizosphere.

There were differences in effect sizes between soils polluted by mixed or single PAHs. Also, soils with mixed PAHs had greater total concentration of PAHs than those contaminated with single PAHs. However, no difference in PAH dissipation between soils with mixed or single PAHs was detected, indicating that 'the rhizosphere effect' influencing each PAH compound was not inhibited by the joint effect of PAHs in soils. Previous studies highlighted the interactive effect of PAHs with other pollutants (Altenburger et al., 2004; Goncalves et al., 2008), but the information on joint effects of different PAHs was lacking.

In order to quantify the relationship between experimental conditions and effect sizes, we tested dose variables, including the single and total concentrations of PAHs, aging and culture periods, and soil characteristics. In PAH dissipation analysis, the fit to the model was significant with duration of plant culture, soil CEC and organic carbon, and was marginally significant with the time of aging. In contrast, the relationships between effect sizes of either single or mixed dose variables and soil pH were weak.

The adsorption sites in soil affect the bioavailability of PAHs significantly. Organic matter, such as humic substances and lignin, would contribute most adsorption sites for PAHs (Chai et al., 2007; Ran et al., 2007; Jonker, 2008). As a result, the dissipation of PAHs correlated significantly with soil CEC and organic matter content.

The present results suggest that the correlation between PAH doses (either single or mixed) and dissipation was not significant. This finding contrasted with the conclusions in many studies that PAH dissipation was dose-related. High PAH doses dissipate proportionally faster than low doses because of the greater bioavailability of PAHs. Our results, however, represent effect sizes, which compared the difference between the treatment group and the control group. This index reflects the effect of rhizosphere on PAH dissipation, which correlated poorly with the PAH doses. In the plant growth analysis, the regression term involving PAH dissipation was significant in the aging time model and the single PAH dose model in shoot growth analysis, and in all models except the aging time one in root growth analysis. The residual errors were, however, highly significant, suggesting that the fit to the model was poor. These analyses did not detect a strong relationship between effect sizes and dose variables, aging time, culture period, and soil characteristics in PAH dissipation and plant growth analyses, except for the soil CEC and organic carbon content influencing PAH dissipation. Inter-species variation in conjunction with experimental variation may have obscured some possible relationships in our analyses.

5. Conclusion

To our knowledge, this study represents the first quantitative evidence of the promoting impact of plants on PAH dissipation and the abundance of PAH decomposers, as well as negative influence of PAHs on plant growth. Traditional reviews of phytoremediation emphasize the variation among species, habitats, and contamination types and doses, whereas our analyses not only captured this variation through the distribution of effect sizes but also revealed a significant promoting effect of the rhizosphere despite all this variation. The dynamics of rhizosphere effects and the resultant PAH dissipation in the soil matrix are complex. The rhizosphere effects are influenced by many factors, including root exudates, microbial communities, soil structure, root architecture, water and nutrient conditions, and pollutant stress. These factors may vary widely among different studies, species, and developmental stages; however, analyses presented here emphasize the generality of a promoting effect of the rhizosphere. The most important result of these analyses is the consistency of the mean effect sizes regardless of other influencing variables in each study.

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Appendix. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envpol.2009.09.024.

Reference

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