Is bioremediation of PAH-contaminated soils worth it? Implications for human health and cancer risk

Cleo Davie-Martin, Kelly Stratton, Justin Teeguarden, Katrina Waters, and Staci Massey Simonich

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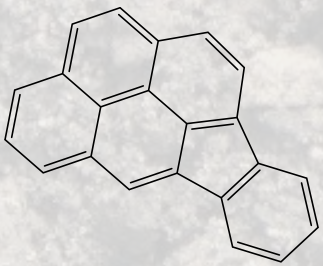
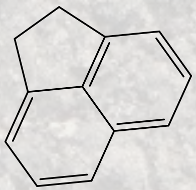
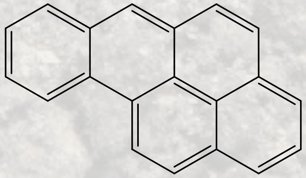
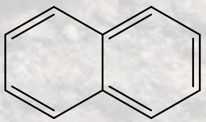




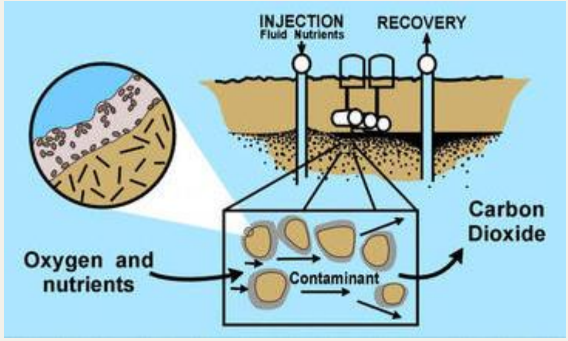




Introduction to Bioremediation

Polycyclic aromatic hydrocarbons (PAHs) are common pollutants in soils

Bioremediation utilizes microorganisms to facilitate the degradation of PAHs into less toxic materials (e.g., CO_2, methane, water)



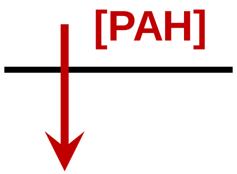
http://bioremediationmadesimple.weebly.com/

- Amendments such as nutrients, surfactants, and exotic microbes boost degradation
- Inexpensive + ‘greener’ + less infrastructure than alternative remediation technologies

Utilized at only **6%** of Superfund source treatment projects (*in situ* and *ex situ*) between 2009-2011 (USEPA, 2013)

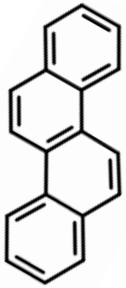
Bioremediation often fails to sufficiently degrade the most carcinogenic PAHs and can initiate formation of more polar metabolites

Monitoring Bioremediation Success

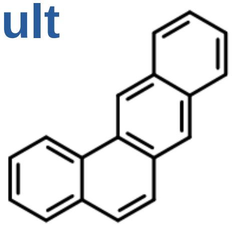


1. Targeted measurements of Σ_{16}PAH concentrations
2. Risk assessment generally includes calculation of an **excess lifetime cancer risk (ELCR):**

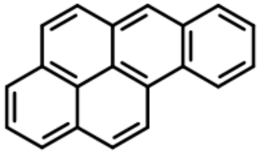
→ Predicts an **‘incidence’ rate** of cancer in exposed populations

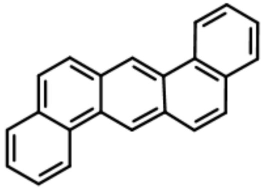


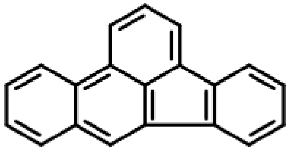
→ **Non-dietary ingestion** is the primary exposure route for **adult** workers exposed to **industrial soils**

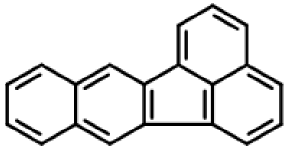


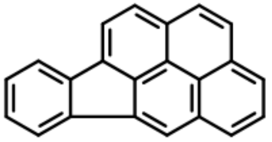
→ Focuses on **eight B2 group PAHs (4-6 rings)** highlighted as known, possible, or probable carcinogens











We collated data from the literature to investigate human health outcomes regarding the cancer risk associated with PAH-contaminated soils.

OBJECTIVES

1. Identify the most effective bioremediation strategies for degrading carcinogenic PAHs

2. Determine if the cancer risk associated with PAH-contaminated soils is reduced following bioremediation

3. Assess the human health implications of remediated soil using cancer risk estimates

METHODS

Collate data from literature: [PAH] pre- and post-bioremediation

Collated Literature Dataset

26 manuscripts = 180 soil bioremediation treatments

Criteria:

- Published *after* 1997
- Bioremediation of contaminated *soils* only ($[PAH]_{total}$ >50 mg kg^{-1})
- PAHs quantified using well-established analytical techniques
- $[PAH]_{soil}$ reported pre- *and* post-bioremediation
- Mean concentrations ± SD reported for *individual* PAHs
- At least 5 of the 8 carcinogenic B2 group PAHs were reported

When criteria weren't (quite) met:

- Authors were asked to provide original datasets (post-2010 publications)
- Follow-up emails were sent after 2 weeks without a response
- 12 authors contacted (regarding15 manuscripts)
- **3 authors provided the necessary data**

METHODS

Define different bioremediation treatment types

Collate data from literature: [PAH] pre- and post-bioremediation

Bioremediation Treatment Types

Lowest degradation potential

1. Killed control: sterilized soil (autoclaving/mercuric chloride)

2. No additions: indigenous microbiota (moisture/aeration only)

3. Biostimulation: addition of nutrient fertilizers

4. Bioaugmentation: soil inoculated with bacterial/fungal colonies

5. Surfactant: addition of (bio)surfactants

6. Composting: addition of organic matter

Highest degradation potential

METHODS

Define different bioremediation treatment types

Calculate percent degradation and ELCR estimates

Collate data from literature: [PAH] pre- and post-bioremediation

Excess Lifetime Cancer Risk (ELCR)

Soil ingestion rate
(50 mg d^{-1})

Unit conversion factor
(10^{-6} g μg^{-1})

Oral slope factor for BaP
(7.3 mg kg^{-1} d^{-1})$^{-1}$

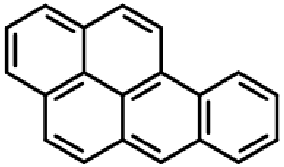
$$\mathrm{ELCR} = \text{constant} \cdot \sum_{i=1}^{n} \left(C_i \cdot \mathrm{RPF}_i \right)$$

Body weight
(70 kg, adult)

Exposure factor (EF) for adults & industrial land:

- 5 days/week
- 50 weeks/year
- For 25 years
- With a life expectancy of 70 years

Excess Lifetime Cancer Risk (ELCR)



Essentially calculating a ***"BaP-equivalent"*** concentration

$$\mathrm{ELCR} = \text{constant} \cdot \sum_{i=1}^{n} (C_i \cdot \mathrm{RPF}_i)$$

PAH_i concentration ($\mu g\ g^{-1}$)

Relative potency factor for PAH_i (relative to BaP)

B2 group PAHs	RPFs
Benzo(a)pyrene (BaP)	**1**
Dibenzo(a,h)anthracene	10
Benzo(b)fluoranthene	0.8
Benzo(a)anthracene	0.2
Indeno(1,2,3-c,d)pyrene	0.07
Benzo(k)fluoranthene	0.03
Chrysene	0.1
Benzo(ghi)perylene	0.009

'Acceptable' health risk
<1 in 1 million people
(10^{-6}) or an **ELCR < 1**

METHODS

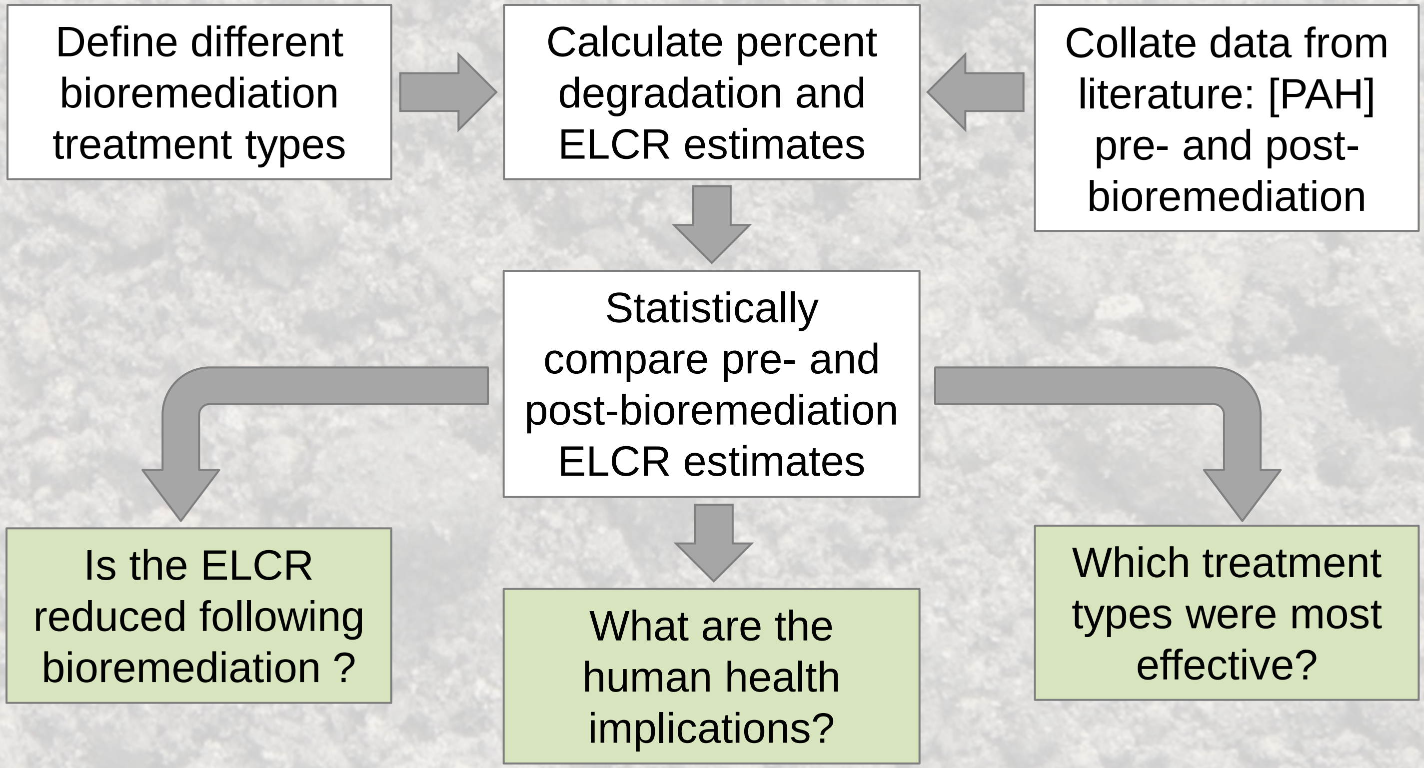
Define different bioremediation treatment types

Calculate percent degradation and ELCR estimates

Collate data from literature: [PAH] pre- and post-bioremediation

Statistically compare pre- and post-bioremediation ELCR estimates

METHODS


Define different bioremediation treatment types
Calculate percent degradation and ELCR estimates
Collate data from literature: [PAH] pre- and post-bioremediation
Statistically compare pre- and post-bioremediation ELCR estimates
Is the ELCR reduced following bioremediation ?
What are the human health implications?
Which treatment types were most effective?

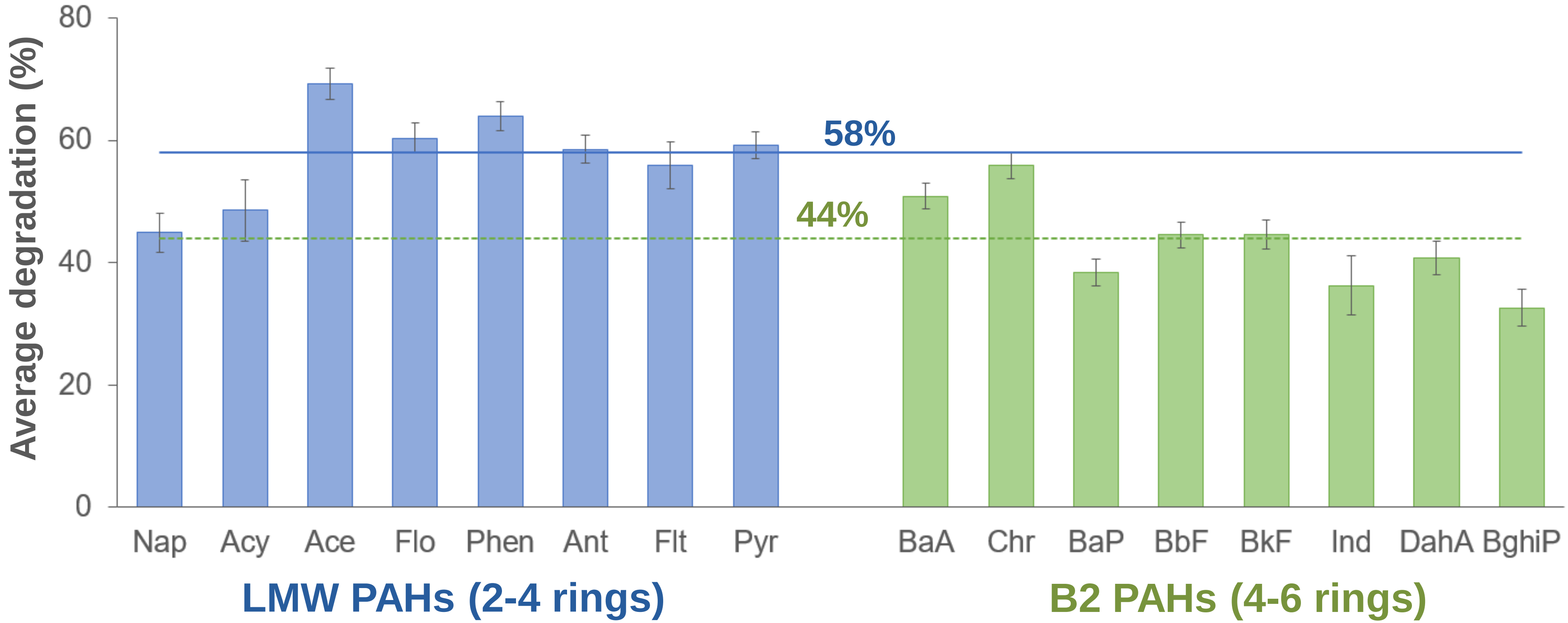
RESULTS

Degradation of Σ_{16}PAHs

Σ_{16}PAH concentrations in soil ↓ following bioremediation, irrespective of treatment type:

→ 2- to 4-ringed LMW PAHs showed the greatest degradation

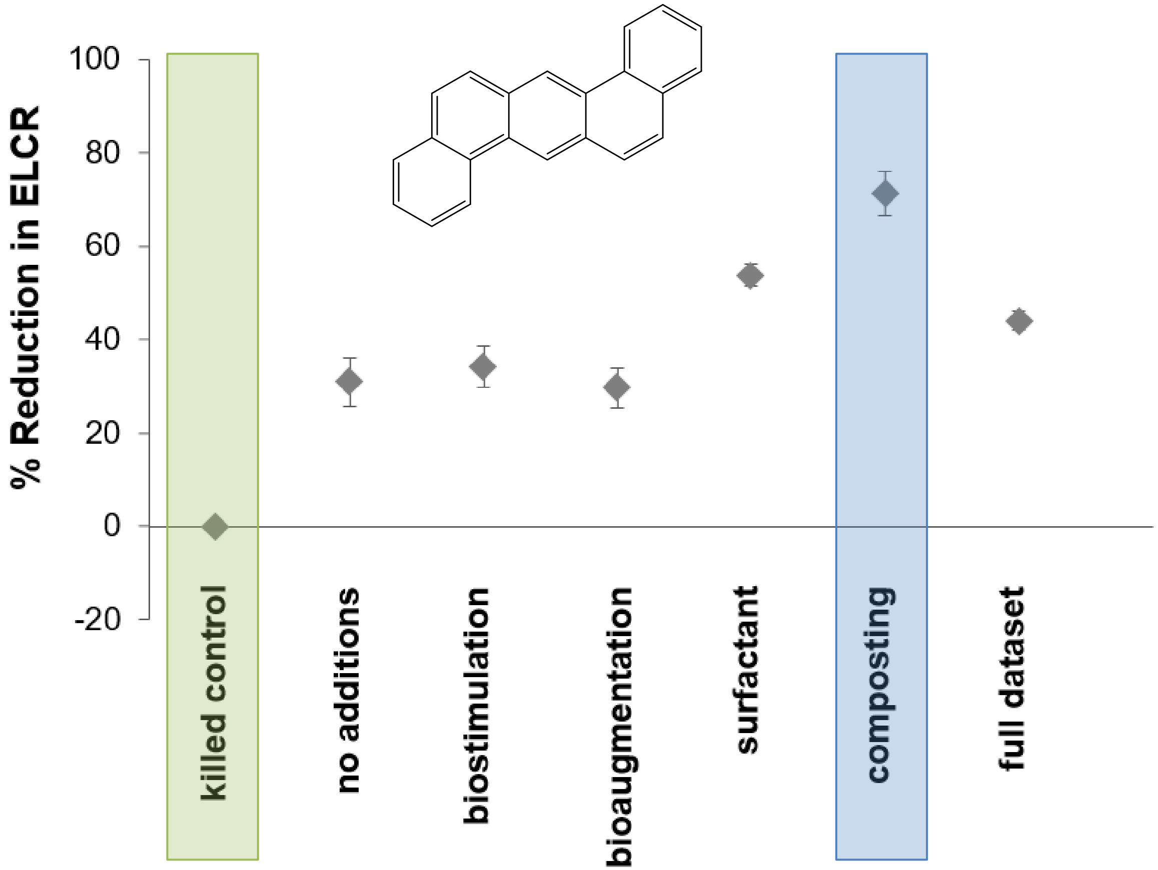
→ 4- to 6-ringed carcinogenic (B2 group) PAHs were degraded to a lesser extent



Reduction in Cancer Risk

Cancer risk was significantly reduced ($p \leq 0.05$) in **160** of the **180** treated soils (89%) following bioremediation

→ Composting treatments were most effective at biodegrading carcinogenic PAHs



→ No reductions in ELCR observed in the killed controls

(∴ no substantial abiotic removal/degradation)

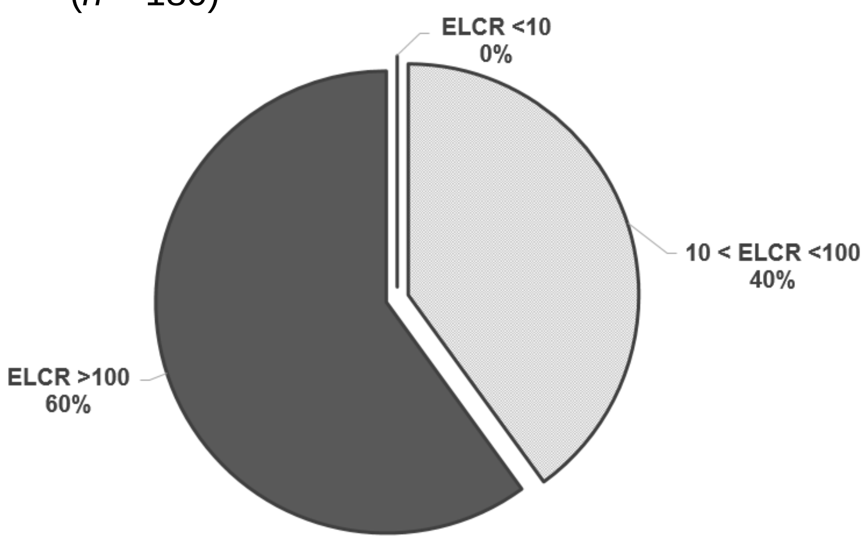
→ DahA largest contributor to ELCR estimates (RPF = 10)

Implications for Human Health

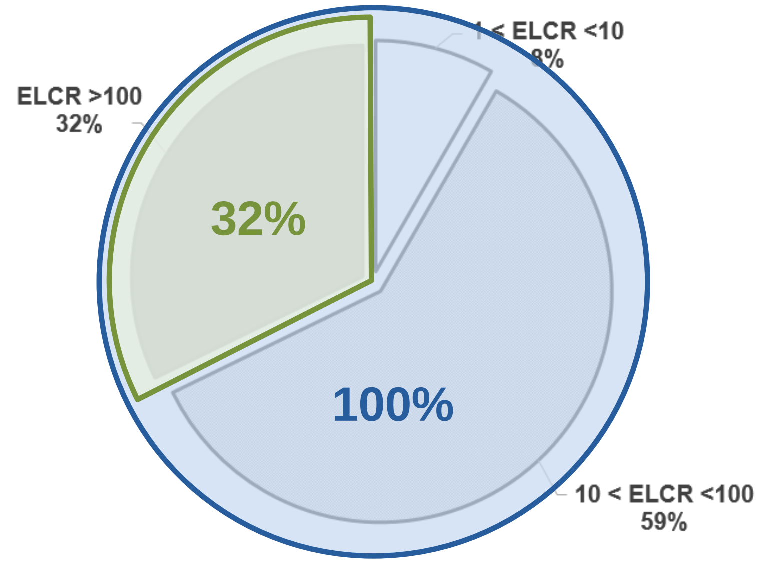
Despite ELCR estimates ↓ post-bioremediation, considerable health risks remain…

USEPA health-based ‘acceptable’ cancer risk level is 10^{-6} **(ELCR < 1)**

Pre-bioremediation
(n = 180)



Post-bioremediation



- All soils had post-bioremediation ELCR values **above the ‘acceptable’ risk level**
- **32%** of treated soils **exceeded USEPA guidelines** by >2 orders of magnitude

Implications for Human Health

- [B2 PAHs] in most of the *treated* soils **exceeded** the USEPA ‘acceptable’ cancer risk concentrations (based on 10^{-6} incidence)

PAHs	#[a]	Industrial soil (mg kg^{-1})	% exceeded (industrial)	Residential soil (mg kg^{-1})	% exceeded (residential)	Ingestion exposure (residential soil) (mg kg^{-1})	% exceeded (ingestion)
Acenaphthene	96	45000	0	3600	0		
Anthracene	140	230000	0	18000	0		
Benzo(a)anthracene	179	2.9	**85**	0.16	**100**	0.21	**100**
Benzo(a)pyrene	179	0.29	**100**	0.016	**100**	0.021	**100**
Benzo(b)fluoranthene	166	2.9	**92**	0.16	**100**	0.21	**100**
Benzo(k)fluoranthene	142	29	25	1.6	**97**	2.1	**92**
Chrysene	169	290	2	16	**54**	21	44
Dibenz(a,h)anthracene	131	0.29	**90**	0.016	**100**	0.021	**100**
Fluoranthene	168	30000	0	2400	0		
Fluorene	122	30000	0	2400	0		
Indeno(1,2,3-cd)pyrene	77	2.9	**70**	0.16	**100**	0.21	**100**
Naphthalene	113	17	**53**	3.8	**75**		
Pyrene	169	23000	0	1800	0		

[a] The number of measurements for each PAH in our collated dataset following bioremediation.

Conclusions

- Composting treatments were *most effective* at biodegrading PAHs and reducing cancer risk, likely due to the nutrients and exotic microflora introduced with compost

- While bioremediation strategies ultimately lower cancer risk, considerable health risks remain:
  - → Often unable to successfully remove carcinogenic PAHs to concentrations below the USEPA health-based ‘acceptable‘ guidelines

- Current strategies for risk assessment focus on the 16 priority PAHs
  - → Mounting evidence that other PAHs and their transformation products may significantly contribute to cancer risk and adverse human health outcomes

- Highlights the need for future bioremediation studies that focus on:
  - → Methods for the enhanced degradation of the most carcinogenic PAHs
  - → Routine measurement and identification of potential transformation products (and their inclusion in future risk assessments)

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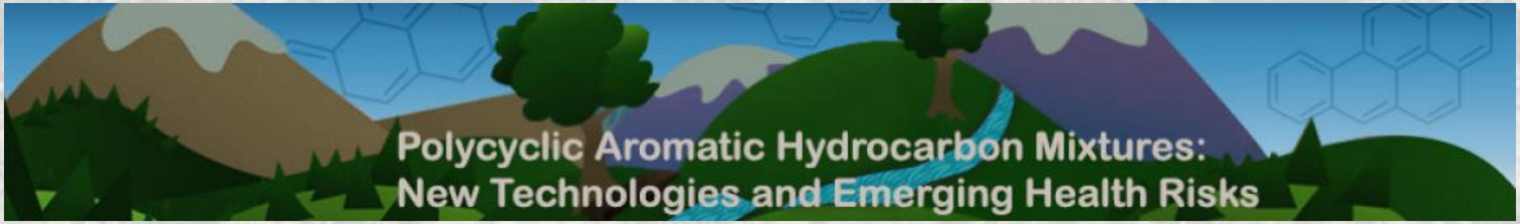


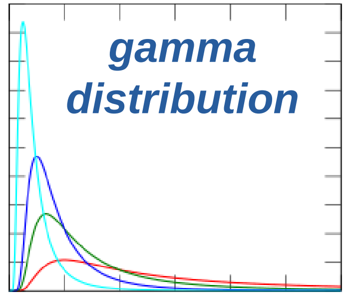
Statistical Comparisons: Simulation Strategy

Pre-bioremediation
(mean ± SD for each PAH_i)

Reconstructed [PAH]
(n = 3, from α and β)

ELCR-pre (n = 3)

repeat *(n = 10 000)*



Post-bioremediation
(mean ± SD for each PAH_i)

Reconstructed [PAH]
(n = 3, from α and β)

ELCR-post (n = 3)

repeat *(n = 10 000)*

Mean of differences in ELCR
(n = 1 & 10 000)

95% bootstrapped
confidence interval (CI)

Null hypothesis: ***H* = 0**
(**no** difference between
pre- and post-ELCR)

Statistical significance?