Tuesday, 1 December 2020

Dear EarthArXiv Editorial Board,

This manuscript entitled “Planted mangroves cap toxic oil spill” has been submitted in Marine Pollution Bulletin. Please note that this manuscript is still under review. Subsequent version of this manuscript may have slightly different content. If accepted, the final version of this manuscript will be available via the “Peer-reviewed Publication DOI” link on the right-hand side of this webpage. Please feel free to contact any of the authors; we do welcome feedback.

Scientific significance
The majority of the studies on crude oil spills report their negative effect on coastal ecosystems, but none have reported on the role of mangrove restoration in immobilising oil spills (one article in Marine Pollution Bulletin has come close; study by Wells (1999) looked at developing biomonitoring tools to assess toxicity of marine environments (including mangroves and PAHs). Mangroves examined in this study were capable of establishing above an oil spill and immobilising an estimated 39.5 tonnes of toxic hydrocarbons per hectare. The toxicity of sediments within the mangrove rhizosphere (0–30 cm) exceeded safety thresholds by up to 190-fold and by up to 220-fold in sediments below mangrove rhizosphere (30–100 cm).

Authors: Pawel Waryszak¹, Maria M. Palacios², Paul E. Carnell³, I. Noyan Yilmaz⁴, and Peter I. Macreadie⁵

Affiliation: Centre for Integrative Ecology. School of Life and Environmental Sciences, Deakin University, Burwood, VIC 3125, Australia.

Emails (1-5)
1. p.waryszak@deakin.edu.au
2. m.palacios@deakin.edu.au
3. paul.carnell@deakin.edu.au
4. noyan.yilmaz@deakin.edu.au
5. p.macreadie@deakin.edu.au

Thank you in advance for receiving our manuscript and considering it for review.

Yours sincerely,

Dr Pawel Waryszak (on behalf of co-authors)
Blue Carbon Lab, Centre for Integrative Ecology
M: (+61) 0410305034. Twitter: @PWaryszak
Planted mangroves cap toxic oil spill

Paweł Waryszak, Maria M. Palacios, Paul E. Carnell, I. Noyan Yilmaz, and Peter I. Macreadie

Centre for Integrative Ecology. School of Life and Environmental Sciences, Deakin University, Burwood, VIC 3125, Australia.

Keywords: total petroleum hydrocarbons, oil spill immobilization, sediment contamination

Abstract

Mangroves are known to provide many ecosystem services, however there is little information on their potential role to cap and immobilise toxic levels of total petroleum hydrocarbons (TPH). Using an Australian case study, we investigated the capacity of planted mangroves (Avicennia marina) to immobilise TPH within a small embayment subjected to multiple oil spills throughout the 1980s. Mangroves were planted on the oil rich strata in 1984 to rehabilitate the site, with 2% surviving to form a dense forest. Sediment core examination down to 1 m deep, revealed mangroves have formed a thick (up to 30 cm) organic layer above the TPH spill (39.5 tonnes ha⁻¹) accumulating on average 6.6 mm of sediments a year. TPH levels below this organic layer are extremely toxic (30,441.6 mg kg⁻¹), exceeding safety thresholds up to 220-fold. This research shows that mangroves can play a valuable role in capping highly toxic oil spill material.

Introduction

Oil spills have caused some of the most devastating degradation to coastal ecosystems worldwide (Beyer et al., 2016; Jafarinejad, 2017). Oil has a long residence time affecting almost all levels of the food web (Balthis et al., 2017; Rohal et al., 2020), smothering coastal vegetation, and degrading soil organic matter (Duke, 2016). Restoration of oil-affected ecosystems is costly, and is unfeasible in many situations (National Research Council, 2013; Wallace et al., 2019).

Mangrove ecosystems provide valuable ecosystem services, such as coastal protection, fisheries enhancement, and carbon sequestration (Barbier et al., 2011; Duncan et al., 2016). However,
their ability to accumulate and trap sediments has not been studied in the context of immobilising oil spillages in the marine environment. Based on the documented ability of mangroves to promote recovery of oil-affected marine food webs (Duke, 2016; Ghizelini et al., 2019), mangroves forests might be able to immobilise the petroleum hydrocarbons belowground within their rhizosphere. Many studies have quantified the toxicity of oil pollutants within sediments of coastal vegetation and reported concentrations of major pollutants such as PAHs (polycyclic aromatic hydrocarbons) as function of their ongoing precipitation (Ashok et al., 2019; Santos et al., 2018). However, none of these studies to our knowledge have evaluated the capacity of planted mangroves to lock away a discrete layer of the polluted sediments.

In this study, we assessed the capacity of planted mangroves to cap and immobilise oil-contaminated sediments by their ability to accrue additional sediment on top of the oil layer. Specifically, we investigated: 1) the ability of planted mangroves to cap and isolate a toxic TPH spill within a discrete sediment layer; and 2) the ability of planted mangroves to survive and thrive by growing and accumulating organic matter above toxic TPH sediments.

Method

Study site

The Stony Creek estuary is located in the Melbourne metropolitan area, Australia (Fig. 1). Stony Creek drains an area of 25 km² of western Victoria’s basalt plains, part of the Maribyrnong catchment (1,408 km²) to Port Philip Bay. The basalt plains were formed approximately 2–5 million years ago and subsequently weathered to produce the overlying clay soils. The land surrounding Stony Creek is naturally occupied by a She-Oak forest (dominated by Allocasuarina verticillata), but was drastically transformed following the European settlement (1850’s) through the establishment of quarries, tanneries, and crude oil storage facilities. Following extensive ecosystem degradation of the native grey mangrove (Avicennia marina), restoration efforts focussed on replanting this indigenous species within its natural distribution (Oliver et al., 2002; Sinclair and Boon, 2012; Whitt et al., 2020).
Aerial images and historical records reveal that the first mangroves were planted in 1984 on the western side of the embayment, and they subsequently expanded to the Northern and Eastern sides (Fig. 1; Fig. S1). According to a local newspaper approximately 15,000 grey mangrove seedlings were planted in 1984 (Scott, 1990). Although only 2% of the mangroves survived due to a subsequent oil spill, they spread through the embayment forming a dense forest.

![Aerial photograph](image1)

**Fig. 1.** A) Stony Creek estuary in south-eastern Australia (37°49'30.5"S, 144°53'48.4"E); B) Aerial photograph in the mid-1980s before the establishment of the mangroves; C) Mangrove seedlings (*Avicennia marina*) planted in 1984 (Photo Credit: Port Places); and D) Satellite image taken in 2019 displaying the three sampling sites.

**Data Collection**

We estimated hydrocarbon content from mangrove sediments at three sampling sites (Fig. 1d). At each sampling site, we collected three soil cores (1 m deep or until bedrock was reached) using a PVC pipe (5 cm internal diameter, 120 cm length) to profile the hydrocarbon content within the
sediment. Nine sediment cores (collected on 03/July/2019) were immediately transported to Deakin University (Burwood campus) and sliced at six depth intervals: 0–10, 10–20, 20–30, 30–50, 50–75 and 75–100 cm. Wet sediment samples were stored at 4°C and shipped to the Analytical Reference Laboratory (Welshpool, Western Australia) for total petroleum hydrocarbon (TPH) and polyaromatic hydrocarbons (PAH) analyses in accordance with the US EPA 3550C methodology (US EPA, 2007). TPH concentration included five hydrocarbon compound groups (TPH C_{6-9}, TPH C_{10-14}, TPH C_{15-28}, TPH C_{29-36}, TPH C_{>36}) and was quantified using gas chromatography / Flame Ionization Detector (Varian CP-3800-4 / Agilent 7890A GC) as described in the Australian national guidelines (National Environment Protection, 1999). Additionally, we quantified 17 PAHs recognised as major pollutants (Tam et al., 2001). The aromatic fractions containing individual PAHs were prepared and analysed following US EPA Method 8270 D (US EPA, 2014), using a Varian 3800 or a Varian 3900 gas chromatograph system, both fitted with Saturn 2000/2100 ion trap detector and using the same column systems.

The dry content of PAHs and TPH and soil organic matter in mangrove sediments was estimated from nine additional cores collected at the three mangrove sites. These additional soil cores were sliced at compatible intervals and dried at 60°C (until a consistent weight was achieved). The organic matter was estimated by looking at the organic carbon in the sediments above the oil spill prior mangrove arrival (establishment horizon). Mangrove arrival times were clearly delineated within the sediments at 30, 14 and 8 cm depth, which corresponded with mangrove arrival at our sampling sites in 1984 (Site 1), 2002 (Site 2) and 2006 (Site 3), respectively. After grinding the dry soil samples, they were subjected to an effervescence test by addition of 12M HCl to examine the presence of inorganic carbon (CaCO_3). One sample contained CaCO_3 and was excluded from further analysis. An elemental C:N analyser (EuroEA 3000 Series) was used to quantify soil organic carbon (%) according to the classical Pregl-Dumas method (Bong and Lee, 2007). Data are available from Mendeley Data Repository (Waryszak et al., 2020).
Data analysis

Contamination characteristics

TPH and PAH toxicities were estimated against high sediment quality guideline values (SQGV) issued by Australian and New Zealand Environment and Conservation Council and the Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ and ANZECC, 2000), as revised by Simpson (2013). The SQGV represent the threshold values associated with adverse biological effects (Warne et al., 2018), which are 280 mg kg\(^{-1}\) for TPHs and at 50 mg kg\(^{-1}\) for PAHs. Following Simpson & Batley (2016), we assessed the toxicity of PAH concentrations against SQGV by normalising to 1% of total organic carbon (OC). PAH concentrations are normalized to OC (%) as PAHs bind to soil organic carbon, making the PAHs less available to aquatic life, thus lessening their toxicity. For example, if the mangrove sediment contained 5 mg kg\(^{-1}\) of total PAHs and 0.55% OC, then 1% OC normalised concentration = 5/0.55 = 9.1 mg kg\(^{-1}\) of total PAHs (1% OC) within the limit of 0.2—10% (Simpson and Batley, 2016). TPH concentrations in relation to sediment depths was assessed with use of a linear regression on untransformed data. TPH and PAH concentrations detected as below a 0.1 mg kg\(^{-1}\) level were converted to 0.05 mg kg\(^{-1}\) for computational purposes.

Correlation between PAH and TPH concentrations were assessed with a Pearson’s correlation test as indicator if sediment pollution occurred in one or multiple spill events. Additionally, the ratio of fluoranthene:pyrene was assessed as an indicator of PAH source in contaminated sediments i.e., petrogenic versus non-petrogenic (e.g. from tanneries). TPH stocks (tonnes ha\(^{-1}\)) were calculated in relation to the oil horizon identified in sediments (below and total). TPH total stock (down to 1 m) and TPH below establishment horizon (capped by organic carbon accumulated above) were compared using regressions.

Capping capability

We assessed the ability of mangroves to cap contaminated sediments by measuring sediment accumulation above the TPH spill and within the detected rhizosphere (top 30 cm). Sediment
accumulation rate (mm year\(^{-1}\)) was estimated from \(^{210}\)Pb concentration profiles across the top 30 cm sediments within three mangrove stands (at each site). The fine fraction of the sediment samples (<63 μm) was analysed by alpha spectrometry following method by Sanchez-Cabeza et al. (1998). Sediment accumulation rates were calculated with the Constant Flux: Constant Sedimentation (CF:CS) model (Krishnaswamy et al., 1971). We reported organic matter (%) in the top 30 cm of sediments from organic carbon values (%) acquired in elemental C:N analyser with use of “Van Bemmelen factor” of 1.724 (Allison, 1965).

Results

Contamination characteristics

Mangrove sediment cores at Stony Creek were characterised by a thick rhizome layer extending until 30 cm depth, followed by a distinct anoxic oil-contaminated layer at 30–50 cm, and a mixture of petroleum and clay soil located between the 50-100 cm depth (Fig. 2). The TPH concentrations were significantly above the biologically safe threshold at all depths and sites with exception of five samples below 75 cm (Fig. 2a). The maximum TPH toxicity was detected at 30–50 cm depth and exceeded SQGV thresholds 220-fold (at Site 1, Fig. 1). This TPH value was significantly higher compared to other depth intervals (\(t = 4.93, P < 0.01\), Table S3). Overall, the concentration of TPH and ranged between 1.6–61,657 mg kg\(^{-1}\). Average estimated TPH stock below 30 cm was 39.5 tonnes ha\(^{-1}\) (±12.1 SE) and in the entire sediment profile (down to 1m deep) amounted to 42.7 tonne ha\(^{-1}\) (±6.9 SE). The total PAH comprised on average 0.2% (±0.03 SE) of TPH (Table S1, Table S2) and PAH concentrations were strongly correlated with TPH (\(R^2=0.76, P<0.001\)). The PAH concentrations did not exceed the SQGV threshold at any of the sampling sites nor depths and ranged between 0.42–35.5 mg kg\(^{-1}\).

Concentrations of TPH and PAH were similar across all sampling depths with an exception of sediments at 30-50 cm depth that contained on average significantly higher concentration of TPH (30,441.6 mg kg\(^{-1}\), Table S1, Fig. 2, Fig. S2). The most frequent component of TPH were hydrocarbons.
with C-chain size of 15 to 28 carbon molecules accounting for 58% (±2 SE) of all TPH (Fig. S2, Fig. 3). Within total PAH, Pyrene was the most abundant component with an average frequency of 20% (±2 SE, Fig. 3). The average pyrene concentration was 38 times higher than the least abundant PAH type Acenaphthene (Fig. 3). The median fluoranthene:pyrene ratio was 0.06 (range: 0.003–1).

**Fig. 2.** Concentration of a) TPH and b) PAH (normalized to 1% of organic matter) in a 0-100 cm soil depth profile at the Stony Creek estuary, Australia. Vertical dotted lines indicate SQGV toxicity.
level associated with adverse biological effects (280 mg kg\(^{-1}\) for TPHs and at 50 mg kg\(^{-1}\) for PAHs).

Values denote average ±SE.
Fig. 3 Concentrations of TPH (TPH C_{6-9}, TPH C_{10-14}, TPH C_{15-28}, TPH C_{29-36}, TPH C_{36+}) and PAH: Naphthalene (Nap), 2-Methylnaphthalene (Met), Acenaphthylene (Acy), Acenaphthene (Ace), Fluorene (Flu), Phenanthrene (Phe), Anthracene (Ant), Fluoranthene (Flt), Pyrene (Pyr), Benz(a)anthracene (BaA), Chrysene (Chr), Benzo(b)fluoranthene (BbF), Benzo(k)fluoranthene (Bkf),
Benzo(a)pyrene (BaP), Indeno(1,2,3-c,d)pyrene (IcdP), Dibenz(a,h)anthracene (DahA), Benzo(ghi)perylene (BghiP), at Stony Creek, Australia. See Table S1 and S2 for detailed information on the relative TPH and PAH content in the sediments (1 m soil profile). Values denote average ±SE. Note different scaling of x-axes.

**Capping capability**

Rate of sedimentation at planted mangroves sites, as detected in the top 30 cm, was on average 6.6 mm year\(^{-1}\) (±0.6 SE) Organic matter content was highest in the top 0–10 cm of sediments (24.2% ±1.5 SE) and gradually decreased with depth: 15% ±0.9 SE at 10–20 cm and 10.6% ±0.8 SE at 20–30 cm.

**Discussion and conclusions**

This study demonstrates the ability of planted mangroves to cap an oil spill that exceeded SQGV toxicity thresholds by up to 220-fold. We found that mangroves successfully established on top of the oil-contaminated sediments (30–50 cm depth, dating back to 1980’s) accumulating relatively high organic matter content within rhizosphere (~16.6% in top 30 cm) and supporting sediment accretion at a rate within the range found in natural mangroves (Ellison, 1999). The high accumulation of sediments was reported in previous studies in relation to mangroves ability to trap marine pollutants (Ashok et al., 2019; Bird, 1986) but has not been reported in relation to their capping service. Here, the characteristics of the site may have facilitated the capacity of mangroves to cap an oil spill. For example, sites that experience naturally high sediment deposition due to the hydrology may allow the oil to settle in such a location. By then planting mangroves at such a site may further help to immobilise and remediate affected sediments. In this study, oil spill was located on impermeable basalt bedrock and likely in-filled with clay soil substrate prior mangrove planting.

Interestingly, the top 30 cm of mangrove rhizosphere also showed high TPH pollution suggesting an upward sorption of oil contaminants (from highly polluted 30–50 cm depth) likely driven by the expanding rhizosphere itself (Patowary et al., 2017). Concentration of TPH pollutants on these
top layers was on average 29-fold above the toxicity threshold (max. 190-fold) and four times above the intervention value (2000 mg kg$^{-1}$) that indicates immediate soil remediation action (Pinedo et al., 2013).

The high toxicity at these study sites was not driven by any of the analysed PAHs, as their concentrations were below safety thresholds. It is likely that the low PAH concentration is related to the susceptibility of PAH components to physical weathering in intertidal conditions. For example, a study by Ke (2002) suggests PAH concentrations may decrease by 56% within three months of a mangrove oil spill. Given PAHs in this study were still detectable ~35 years after the spill, suggests that PAH concentration was high in the past, enabling us to assess their source presently. For example, the low ratio of two indicator PAH types, fluoranthene:pyrene (<1), suggests strong petrogenic origin of the oil spill (Tam et al., 2001). Similarly, the consistent TPH:PAH ratio distribution in the sediments suggests that the pollutants originated from the same source and within a relatively short period of time, given that weathering processes and oil spill chemical characterisation are a function of time and oxidation levels (Tarr et al., 2016; Wang and Fingas, 2003).

Our results show that mangrove forests may be capable of immobilizing high volumes of toxic petroleum hydrocarbons given their ability to accumulate sediments above the discrete layer of oil-contaminated sediments. However, extreme sea level-related events may pose risk to planted mangroves (Lovelock et al., 2017). To prevent a potential mangrove dieback and the release of hydrocarbons into the coastal environment, it is critical to put in place remediation actions and plans to protect and monitor mangroves (Newton et al., 2020; Ossai et al., 2020). Some potential remediation approaches include the use of hydrocarbon-degrading microbial communities (Daccò et al., 2020; Kumar et al., 2019; Machado et al., 2019), the removal and oxidation of contaminated sediments (Iturbe et al., 2004), the introduction of biochar into affected sediments (Mukome et al., 2020), or phytoremediation involving additional mangrove planting combined with hydrocarbon-degrading microorganisms (Verâne et al., 2020). Climate change, along with the rising sea level, and increasing intensity of storms are already accelerating the degradation and loss of mangrove
ecosystems worldwide (Duke et al., 2017; Zhang et al., 2019). The disturbance or loss of the Stony Creek mangrove forest and the subsequent release of toxic sediments, could have devastating repercussions to coastal fauna and flora.

Acknowledgements

We are grateful to the effort and enthusiasm of the ~60 citizen scientists that joined the #BlueCarbonArmy and supported the data collection activities at Stony Creek, Australia. We also thank Dr Maria Garcia for her support overseeing the field sampling. This research was funded by HSBC and Deakin University in partnership with Earthwatch Institute Australia.

References

Allison, L.E., 1965. Organic Carbon. Methods Soil Anal., Agronomy Monographs. https://doi.org/doi:10.2134/agronmonogr9.2.c39

ARMCANZ, ANZECC, 2000. Australian and New Zealand Guidelines for Fresh and Marine Water Quality [WWW Document]. URL https://www.waterquality.gov.au/anz-guidelines/resources/previous-guidelines/anzecc-armcanz-2000

Ashok, A., Cusack, M., Saderne, V., Krishnakumar, P.K., Rabaoui, L., Qurban, M.A., Duarte, C.M., Agustí, S., 2019. Accelerated burial of petroleum hydrocarbons in Arabian Gulf blue carbon repositories. Sci. Total Environ. 669, 205–212.

Balthis, W.L., Hyland, J.L., Cooksey, C., Montagna, P.A., Baguley, J.G., Ricker, R.W., Lewis, C., 2017. Sediment quality benchmarks for assessing oil-related impacts to the deep-sea benthos. Integr. Environ. Assess. Manag. 13, 840–851. https://doi.org/10.1002/ieam.1898

Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., Silliman, B.R., 2011. The value of estuarine and coastal ecosystem services. Ecol. Monogr. 81, 169–193. https://doi.org/10.1890/10-1510.1

Beyer, J., Trannum, H.C., Bakke, T., Hodson, P. V, Collier, T.K., 2016. Environmental effects of the Deepwater Horizon oil spill: A review. Mar. Pollut. Bull. 110, 28–51. https://doi.org/https://doi.org/10.1016/j.marpolbul.2016.06.027

Bird, E.C.F., 1986. Mangroves and intertidal morphology in Westernport Bay, Victoria, Australia. Mar. Geol. 69, 251–271. https://doi.org/https://doi.org/10.1016/0025-3227(86)90042-3

Bong, Y.S., Lee, K.S., 2007. A fast, simple calibration method for organic carbon isotope analysis using continuous-flow elemental analyzer interfaced with an isotope ratio mass spectrometer. Anal. Sci. 23, 1447–1449. https://doi.org/10.2116/analsci.23.1447

Daccò, C., Girometta, C., Asemoloye, M.D., Carpani, G., Picco, A.M., Tosi, S., 2020. Key fungal degradation patterns, enzymes and their applications for the removal of aliphatic hydrocarbons in polluted soils: A review. Int. Biodeterior. Biodegradation 147, 104866. https://doi.org/https://doi.org/10.1016/j.ibiod.2019.104866
Duke, N.C., 2016. Oil spill impacts on mangroves: recommendations for operational planning and action based on a global review. Mar. Pollut. Bull. 109, 700–715.

Duke, N.C., Kovacs, J.M., Griffiths, A.D., Preece, L., Hill, D.J.E., van Oosterzee, P., Mackenzie, J., Morning, H.S., Burrows, D., 2017. Large-scale dieback of mangroves in Australia’s Gulf of Carpentaria: a severe ecosystem response, coincidental with an unusually extreme weather event. Mar. Freshw. Res. 68, 1816–1829.

Duncan, C., Primavera, J.H., Pettorelli, N., Thompson, J.R., Loma, R.J.A., Koldewey, H.J., 2017. Rehabilitating mangrove ecosystem services: A case study on the relative benefits of abandoned pond reversion from Panay Island, Philippines. Mar. Pollut. Bull. 109, 772–782. https://doi.org/https://doi.org/10.1016/j.marpolbul.2016.05.049

Ellison, J.C., 1999. Impacts of Sediment Burial on Mangroves. Mar. Pollut. Bull. 37, 420–426. https://doi.org/https://doi.org/10.1016/S0025-326X(98)00122-2

Ghizelini, A.M., Martins, K.G., Gießelmann, U.C., Santoro, E., Pasqualette, L., Mendonça-Hagler, L.C.S., Rosado, A.S., Macrae, A., 2019. Fungal communities in oil contaminated mangrove sediments – Who is in the mud? Mar. Pollut. Bull. 139, 181–188. https://doi.org/10.1016/j.marpolbul.2018.12.040

Iturbe, R., Flores, C., Chavez, C., Bautista, G., Torres, L.G., 2004. Remediation of contaminated soil using soil washing and biopile methodologies at a field level. J. Soils Sediments 4, 115–122. https://doi.org/http://dx.doi.org/10.1007/BF02991055

Jafarinejad, S., 2017. Environmental impacts of the petroleum industry, protection options, and Regulations. Pet. waste Treat. Pollut. Control 85–116.

Ke, L., Wong, T.W.Y., Wong, Y.S., Tam, N.F.Y., 2002. Fate of polycyclic aromatic hydrocarbon (PAH) contamination in a mangrove swamp in Hong Kong following an oil spill. Mar. Pollut. Bull. 45, 339–347.

Krishnaswamy, S., Lal, D., Martin, J.M., Meybeck, M., 1971. Geochronology of lake sediments. Earth Planet. Sci. Lett. 11, 407–414. https://doi.org/https://doi.org/10.1016/0012-821X(71)90202-0

Kumar, A.G., Rajan, N.N., Kirubagaran, R., Dharani, G., 2019. Biodegradation of crude oil using self-immobilized hydrocarbonoclastic deep sea bacterial consortium. Mar. Pollut. Bull. 146, 741–750.

Lovelock, C.E., Feller, I.C., Reef, R., Hickey, S., Ball, M.C., 2017. Mangrove dieback during fluctuating sea levels. Sci. Rep. 7, 1680. https://doi.org/10.1038/s41598-017-01927-6

Machado, L.F., de Assis Leite, D.C., da Costa Rachid, C.T.C., Paes, J.E., Martins, E.F., Peixoto, R.S., Rosado, A.S., 2019. Tracking Mangrove Oil Bioremediation Approaches and Bacterial Diversity at Different Depths in an in situ Mesocosms System. Front. Microbiol. 10, 2107. https://doi.org/10.3389/fmicb.2019.02107

Mukome, F.N.D., Buelow, M.C., Shang, J., Peng, J., Rodriguez, M., Mackay, D.M., Pignatello, J.J., Sihota, N., Hoelen, T.P., Parikh, S.J., 2020. Biochar amendment as a remediation strategy for surface soils impacted by crude oil. Environ. Pollut. 265, 115006. https://doi.org/https://doi.org/10.1016/j.envpol.2020.115006

National Environment Protection, 1999. Assessment of Site Contamination Measure 1999 – Amended 2013 - Volume 4: Schedule B3,Guideline on Laboratory Analysis of Potentially Contaminated Soil.

National Research Council, 2013. An ecosystem services approach to assessing the impacts of the Deepwater Horizon oil spill in the Gulf of Mexico. National Academies Press.

Newton, A., Icely, J., Cristina, S., Perillo, G.M.E., Turner, R.E., Ashan, D., Cragg, S., Luo, Y., Tu, C., Li, Y,
Zhang, H., Ramesh, R., Forbes, D.L., Solidoro, C., Béjaoui, B., Gao, S., Pastres, R., Kelsey, H., Taillie, D., Nhan, N., Brito, A.C., de Lima, R., Kuenzer, C., 2020. Anthropogenic, Direct Pressures on Coastal Wetlands. Front. Ecol. Evol.

Oliver, I., Smith, P.L., Lunt, I., Parkes, D., 2002. Pre-1750 vegetation, naturalness and vegetation condition: What are the implications for biodiversity conservation? Ecol. Manag. Restor. 3, 176–178. https://doi.org/10.1046/j.1442-8903.2002.00110.x

Ossai, I.C., Ahmed, A., Hassan, A., Hamid, F.S., 2020. Remediation of soil and water contaminated with petroleum hydrocarbon: A review. Environ. Technol. Innov. 17, 100526. https://doi.org/https://doi.org/10.1016/j.eti.2019.100526

Patowary, R., Patowary, K., Devi, A., Kalita, M.C., Deka, S., 2017. Uptake of Total Petroleum Hydrocarbon (TPH) and Polycyclic Aromatic Hydrocarbons (PAHs) by Oryza sativa L. Grown in Soil Contaminated with Crude Oil. Bull. Environ. Contam. Toxicol. 98, 120–126. https://doi.org/10.1007/s00128-016-1990-5

Pinedo, J., Ibáñez, R., Lijzen, J.P.A., Irabien, A., 2013. Assessment of soil pollution based on total petroleum hydrocarbons and individual oil substances. J. Environ. Manage. 130, 72–79.

Rohal, M., Barrera, N., Van Eenennaam, J.S., Foekema, E.M., Montagna, P.A., Murk, A.J., Pryor, M., Romero, I.C., 2020. The effects of experimental oil-contaminated marine snow on meiofauna in a microcosm. Mar. Pollut. Bull. 150, 110656. https://doi.org/10.1016/j.marpolbul.2019.110656

Sanchez-Cabeza, J.A., Masqué, P., Ani-Ragolta, I., 1998. 210Pb and 210Po analysis in sediments and soils by microwave acid digestion. J. Radioanal. Nucl. Chem. 227, 19–22. https://doi.org/10.1007/BF02386425

Santos, R.C., Gomes, Gadelha Vieira Santos, L., Santos, E., Cardoso, D.F., Martins, C.J.A., 2018. Polycyclic aromatic hydrocarbons in sediments of the Amazon River Estuary (Amapá, Northern Brazil): Distribution, sources and potential ecological risk. Mar. Pollut. Bull. 135, 769–775.

Scott, G., 1990. Environ. West. Times 4.

Simpson, S., Batley, G., 2016. Sediment quality assessment: A practical guide, CSIRO. https://doi.org/10.1071/9781486303854

Simpson, S.L., Batley, G.E., Chariton, A.A., 2013. Revision of the ANZECC/ARMCANZ Sediment Quality Guidelines. CSIRO.

Sinclair, S., Boon, P.I., 2012. Changes in the area of coastal marsh in Victoria since the mid 19th century. Cunninghamia 12, 153–176.

Tam, N.F.Y., Ke, L., Wang, X.H., Wong, Y.S., 2001. Contamination of polycyclic aromatic hydrocarbons in surface sediments of mangrove swamps. Environ. Pollut. 114, 255–263. https://doi.org/10.1016/S0269-7491(00)00212-8

Tarr, M.A., Zito, P., Overton, E.B., Olson, G.M., Adhikari, P.L., Reddy, C.M., 2016. Weathering of oil spilled in the marine environment. Oceanography 29, 126–135. https://doi.org/10.5670/oceanog.2016.77

US EPA, 2014. Method no 8270D: Semi Volatile Organic Compounds by GCMS Rev 5.

US EPA, 2007. Method No 3550C: Ultrasonic Extraction Rev 3.

Verâne, J., dos Santos, N.C.P., da Silva, V.L., de Almeida, M., de Oliveira, O.M.C., Moreira, Í.T.A., 2020. Phytoremediation of polycyclic aromatic hydrocarbons (PAHs) in mangrove sediments using Rhizophora mangle. Mar. Pollut. Bull. 160, 111687.
Wallace, R.L., Gilbert, S., Reynolds III, J.E., 2019. Improving the Integration of Restoration and Conservation in Marine and Coastal Ecosystems: Lessons from the Deepwater Horizon Disaster. Bioscience 69, 920–927.

Wang, Z., Fingas, M.F., 2003. Development of oil hydrocarbon fingerprinting and identification techniques. Mar. Pollut. Bull. 47, 423–452. https://doi.org/https://doi.org/10.1016/S0025-326X(03)00215-7

Warne, M.S., Batley, G.E., van Dam, R.A., Chapman, J.C., Fox, D.R., Hickey, C.W., Stauber, J.L., 2018. Revised Method for Deriving Australian and New Zealand Water Quality Guideline Values for Toxicants.

Waryszak, P., Palacios, M.M., Carnell, P.E., Yilmaz, I.N., Macreadie, P.I., 2020. “Dataset: Planted mangroves cap toxic oil spill.” https://doi.org/10.17632/8svcpn6vp5.1

Whitt, A.A., Coleman, R., Lovelock, C.E., Gillies, C., Ierodiaconou, D., Liyanapathirana, M., Macreadie, P.I., 2020. March of the mangroves: Drivers of encroachment into southern temperate saltmarsh. Estuar. Coast. Shelf Sci. 240, 106776.

Zhang, B., Matchinski, E.J., Chen, B., Ye, X., Jing, L., Lee, K., 2019. Chapter 21 - Marine Oil Spills—Oil Pollution, Sources and Effects, in: Sheppard, C.B.T.-W.S. an E.E. (Second E. (Ed.), World Seas: An Environmental Evaluation (Second Edition). Academic Press, pp. 391–406. https://doi.org/https://doi.org/10.1016/B978-0-12-805052-1.00024-3

Supplementary Information (appendices)

- Table S1 Concentrations of all TPH and PAH types across sampling depths.
- Table S2 Total TPH stock (tonnes ha⁻¹) and TPH stock below the oil spill horizon.
- Table S3. Effect of sediment depths (cm) on TPH and PAH concentrations.
- Fig. S1 Time-stamped satellite imagery of oil spill study area.
- Fig. S2 Concentrations of TPH (Total TPH, TPH C₆⁻₉, TPH C₁₀⁻₁₄, TPH C₁₅⁻₂₈, TPH C₂₉⁻₃₆, TPH C₃₆⁺) at six depth intervals (0–10, 10–20,20–30, 30–50,50–75 and 75–100 cm).
- Table S1 Average concentrations of all TPH (TPH C₆₋₉, TPH C₁₀₋₁₄, TPH C₁₅₋₂₈, TPH C₂₉₋₃₆, TPH C₃₆) and PAH: Naphthalene (Nap), 2-Methylnaphthalene (Met), Acenaphthylene (Acy), Acenaphthene (Ace), Fluorene (Flu), Phenanthrene (Phe), Anthracene (Ant), Fluoranthene (Flt), Pyrene (Pyr), Benz(a)anthracene (BaA), Chrysene (Chr), Benzo(b)fluoranthene (BbF), Benzo(k)fluoranthene (Bkf), Benzo(a)pyrene (BaP), Indeno(1,2,3-c,d)pyrene (IcdP), Dibenz(a,h)anthracene (DaA), Benzo(ghi)perylene (BghiP). Sediments (1 m soil profile). at Stony Creek, Australia. Total_PAH_norm and Total_TPH denote total concentrations of PAHs and TPHs, respectively. N denotes number of replicates and SE denotes standard error.

| Hydrocarbon type | Sampling depth (cm) | Average concentration (mg kg⁻¹) | N  | SE  | Times above threshold 280 mg kg⁻¹ |
|------------------|---------------------|---------------------------------|----|-----|---------------------------------|
| Ace              | 00_10               | 0.02                            | 9.00 | 0.00 | 0.00                            |
| Ace              | 10_20               | 0.02                            | 9.00 | 0.00 | 0.00                            |
| Ace              | 20_30               | 0.01                            | 9.00 | 0.00 | 0.00                            |
| Ace              | 30_50               | 0.11                            | 9.00 | 0.06 | 0.00                            |
| Ace              | 50_75               | 0.03                            | 9.00 | 0.00 | 0.00                            |
| Ace              | 75_100              | 0.04                            | 6.00 | 0.01 | 0.00                            |
| Acy              | 00_10               | 0.02                            | 9.00 | 0.00 | 0.00                            |
| Acy              | 10_20               | 0.03                            | 9.00 | 0.01 | 0.00                            |
| Acy              | 20_30               | 0.03                            | 9.00 | 0.01 | 0.00                            |
| Acy              | 30_50               | 0.17                            | 9.00 | 0.05 | 0.00                            |
| Acy              | 50_75               | 0.11                            | 9.00 | 0.03 | 0.00                            |
| Acy              | 75_100              | 0.04                            | 6.00 | 0.01 | 0.00                            |
| Ant              | 00_10               | 0.03                            | 9.00 | 0.00 | 0.00                            |
| Ant              | 10_20               | 0.05                            | 9.00 | 0.01 | 0.00                            |
| Ant              | 20_30               | 0.10                            | 9.00 | 0.03 | 0.00                            |
| Ant              | 30_50               | 0.90                            | 9.00 | 0.20 | 0.00                            |
| Ant              | 50_75               | 0.26                            | 9.00 | 0.11 | 0.00                            |
| Ant              | 75_100              | 0.05                            | 6.00 | 0.01 | 0.00                            |
| BaA              | 00_10               | 0.06                            | 9.00 | 0.01 | 0.00                            |
| BaA              | 10_20               | 0.18                            | 9.00 | 0.06 | 0.00                            |
| BaA              | 20_30               | 0.26                            | 9.00 | 0.05 | 0.00                            |
| BaA              | 30_50               | 1.78                            | 9.00 | 0.46 | 0.01                            |
| BaA              | 50_75               | 0.36                            | 9.00 | 0.13 | 0.00                            |
| Compound | Segment | Value 1 | Value 2 | Value 3 | Value 4 |
|----------|---------|---------|---------|---------|---------|
| BaA      | 75_100  | 0.21    | 6.00    | 0.05    | 0.00    |
| BaP      | 00_10   | 0.09    | 9.00    | 0.02    | 0.00    |
| BaP      | 10_20   | 0.23    | 9.00    | 0.07    | 0.00    |
| BaP      | 20_30   | 0.29    | 9.00    | 0.07    | 0.00    |
| BaP      | 30_50   | 1.45    | 9.00    | 0.39    | 0.01    |
| BaP      | 50_75   | 0.79    | 9.00    | 0.21    | 0.00    |
| BaP      | 75_100  | 0.19    | 6.00    | 0.04    | 0.00    |
| BbF      | 00_10   | 0.13    | 9.00    | 0.03    | 0.00    |
| BbF      | 10_20   | 0.30    | 9.00    | 0.10    | 0.00    |
| BbF      | 20_30   | 0.31    | 9.00    | 0.09    | 0.00    |
| BbF      | 30_50   | 1.12    | 9.00    | 0.34    | 0.00    |
| BbF      | 50_75   | 0.61    | 9.00    | 0.23    | 0.00    |
| BbF      | 75_100  | 0.22    | 6.00    | 0.06    | 0.00    |
| BghiP    | 00_10   | 0.04    | 9.00    | 0.00    | 0.00    |
| BghiP    | 10_20   | 0.06    | 9.00    | 0.02    | 0.00    |
| BghiP    | 20_30   | 0.05    | 9.00    | 0.01    | 0.00    |
| BghiP    | 30_50   | 0.17    | 9.00    | 0.05    | 0.00    |
| BghiP    | 50_75   | 0.13    | 9.00    | 0.03    | 0.00    |
| BghiP    | 75_100  | 0.07    | 6.00    | 0.02    | 0.00    |
| BkF      | 00_10   | 0.04    | 9.00    | 0.00    | 0.00    |
| BkF      | 10_20   | 0.06    | 9.00    | 0.02    | 0.00    |
| BkF      | 20_30   | 0.06    | 9.00    | 0.01    | 0.00    |
| BkF      | 30_50   | 0.18    | 9.00    | 0.06    | 0.00    |
| BkF      | 50_75   | 0.13    | 9.00    | 0.04    | 0.00    |
| BkF      | 75_100  | 0.07    | 6.00    | 0.02    | 0.00    |
| Chr      | 00_10   | 0.05    | 9.00    | 0.01    | 0.00    |
| Chr      | 10_20   | 0.13    | 9.00    | 0.04    | 0.00    |
| Chr      | 20_30   | 0.15    | 9.00    | 0.02    | 0.00    |
| Chr      | 30_50   | 1.37    | 9.00    | 0.44    | 0.00    |
| Chr      | 50_75   | 0.22    | 9.00    | 0.07    | 0.00    |
| Chr | DahA | 00_10 | 0.04 | 9.00 | 0.00 | 0.00 |
|-----|------|-------|------|------|------|------|
|     | DahA | 10_20 | 0.03 | 9.00 | 0.00 | 0.00 |
|     | DahA | 20_30 | 0.03 | 9.00 | 0.00 | 0.00 |
|     | DahA | 30_50 | 0.06 | 9.00 | 0.01 | 0.00 |
|     | DahA | 50_75 | 0.06 | 9.00 | 0.01 | 0.00 |
|     | DahA | 75_100| 0.07 | 6.00 | 0.02 | 0.00 |
|     | Flt  | 00_10 | 0.06 | 9.00 | 0.02 | 0.00 |
|     | Flt  | 10_20 | 0.23 | 9.00 | 0.07 | 0.00 |
|     | Flt  | 20_30 | 0.31 | 9.00 | 0.06 | 0.00 |
|     | Flt  | 30_50 | 2.46 | 9.00 | 0.61 | 0.01 |
|     | Flt  | 50_75 | 0.82 | 9.00 | 0.23 | 0.00 |
|     | Flt  | 75_100| 0.29 | 6.00 | 0.09 | 0.00 |
|     | Flu  | 00_10 | 0.02 | 9.00 | 0.00 | 0.00 |
|     | Flu  | 10_20 | 0.02 | 9.00 | 0.00 | 0.00 |
|     | Flu  | 20_30 | 0.02 | 9.00 | 0.01 | 0.00 |
|     | Flu  | 30_50 | 0.23 | 9.00 | 0.09 | 0.00 |
|     | Flu  | 50_75 | 0.04 | 9.00 | 0.01 | 0.00 |
|     | Flu  | 75_100| 0.04 | 6.00 | 0.01 | 0.00 |
|     | IcdP | 00_10 | 0.06 | 9.00 | 0.01 | 0.00 |
|     | IcdP | 10_20 | 0.07 | 9.00 | 0.03 | 0.00 |
|     | IcdP | 20_30 | 0.06 | 9.00 | 0.01 | 0.00 |
|     | IcdP | 30_50 | 0.21 | 9.00 | 0.06 | 0.00 |
|     | IcdP | 50_75 | 0.17 | 9.00 | 0.04 | 0.00 |
|     | IcdP | 75_100| 0.07 | 6.00 | 0.02 | 0.00 |
|     | Met  | 00_10 | 0.02 | 9.00 | 0.00 | 0.00 |
|     | Met  | 10_20 | 0.04 | 9.00 | 0.01 | 0.00 |
|     | Met  | 20_30 | 0.04 | 9.00 | 0.01 | 0.00 |
|     | Met  | 30_50 | 0.23 | 9.00 | 0.09 | 0.00 |
|     | Met  | 50_75 | 0.06 | 9.00 | 0.02 | 0.00 |
| Compound | Time Range | Mean Value | Median Value | Minimum Value | Maximum Value |
|----------|------------|------------|--------------|---------------|---------------|
| Met      | 75_100     | 0.04       | 6.00         | 0.01          | 0.00          |
| Nap      | 00_10      | 0.02       | 9.00         | 0.00          | 0.00          |
| Nap      | 10_20      | 0.03       | 9.00         | 0.01          | 0.00          |
| Nap      | 20_30      | 0.03       | 9.00         | 0.01          | 0.00          |
| Nap      | 30_50      | 0.15       | 9.00         | 0.04          | 0.00          |
| Nap      | 50_75      | 0.06       | 9.00         | 0.01          | 0.00          |
| Nap      | 75_100     | 0.04       | 6.00         | 0.01          | 0.00          |
| Phe      | 00_10      | 0.05       | 9.00         | 0.01          | 0.00          |
| Phe      | 10_20      | 0.15       | 9.00         | 0.05          | 0.00          |
| Phe      | 20_30      | 0.15       | 9.00         | 0.03          | 0.00          |
| Phe      | 30_50      | 0.48       | 9.00         | 0.09          | 0.00          |
| Phe      | 50_75      | 0.35       | 9.00         | 0.10          | 0.00          |
| Phe      | 75_100     | 0.20       | 6.00         | 0.08          | 0.00          |
| Pyr      | 00_10      | 0.08       | 9.00         | 0.02          | 0.00          |
| Pyr      | 10_20      | 0.29       | 9.00         | 0.09          | 0.00          |
| Pyr      | 20_30      | 0.92       | 9.00         | 0.27          | 0.00          |
| Pyr      | 30_50      | 4.89       | 9.00         | 1.26          | 0.02          |
| Pyr      | 50_75      | 1.88       | 9.00         | 0.72          | 0.01          |
| Pyr      | 75_100     | 0.33       | 6.00         | 0.10          | 0.00          |
| Total_PAH_norm | 00_10 | 0.84 | 9.00 | 0.11 | 0.00 |
| Total_PAH_norm | 10_20 | 1.91 | 9.00 | 0.55 | 0.01 |
| Total_PAH_norm | 20_30 | 2.81 | 9.00 | 0.59 | 0.01 |
| Total_PAH_norm | 30_50 | 15.96 | 9.00 | 3.82 | 0.06 |
| Total_PAH_norm | 50_75 | 6.08 | 9.00 | 1.49 | 0.02 |
| Total_PAH_norm | 75_100 | 2.08 | 6.00 | 0.44 | 0.01 |
|                |        |          |          |          |          |
|----------------|--------|----------|----------|----------|----------|
| Total_TPH      | 00_10  | 3834.86  | 9.00     | 659.96   | 13.70    |
| Total_TPH      | 10_20  | 5385.97  | 9.00     | 1045.51  | 19.24    |
| Total_TPH      | 20_30  | 14814.69 | 9.00     | 5130.47  | 52.91    |
| Total_TPH      | 30_50  | 30441.67 | 9.00     | 5396.28  | 108.72   |
| Total_TPH      | 50_75  | 10481.08 | 9.00     | 5004.21  | 37.43    |
| Total_TPH      | 75_100 | 125.18   | 6.00     | 63.84    | 0.45     |
| TPH_06to09     | 00_10  | 0.41     | 9.00     | 0.02     | 0.00     |
| TPH_06to09     | 10_20  | 0.26     | 9.00     | 0.01     | 0.00     |
| TPH_06to09     | 20_30  | 0.23     | 9.00     | 0.02     | 0.00     |
| TPH_06to09     | 30_50  | 0.24     | 9.00     | 0.02     | 0.00     |
| TPH_06to09     | 50_75  | 0.23     | 9.00     | 0.01     | 0.00     |
| TPH_06to09     | 75_100 | 0.23     | 6.00     | 0.01     | 0.00     |
| TPH_10to14     | 00_10  | 13.71    | 9.00     | 11.04    | 0.05     |
| TPH_10to14     | 10_20  | 19.97    | 9.00     | 6.14     | 0.07     |
| TPH_10to14     | 20_30  | 142.32   | 9.00     | 50.71    | 0.51     |
| TPH_10to14     | 30_50  | 657.71   | 9.00     | 138.25   | 2.35     |
| TPH_10to14     | 50_75  | 275.84   | 9.00     | 145.81   | 0.99     |
| TPH_10to14     | 75_100 | 0.77     | 6.00     | 0.41     | 0.00     |
| TPH_15to28     | 00_10  | 1666.28  | 9.00     | 208.76   | 5.95     |
| TPH_15to28 | 10_20 | 2783.78 | 9.00 | 598.80 | 9.94 |
| TPH_15to28 | 20_30 | 8728.04 | 9.00 | 3105.63 | 31.17 |
| TPH_15to28 | 30_50 | 21511.70 | 9.00 | 4120.69 | 76.83 |
| TPH_15to28 | 50_75 | 7267.28 | 9.00 | 3563.20 | 25.95 |
| TPH_15to28 | 75_100 | 88.88 | 6.00 | 48.84 | 0.32 |
| TPH_29to36 | 00_10 | 1454.50 | 9.00 | 294.51 | 5.19 |
| TPH_29to36 | 10_20 | 1826.15 | 9.00 | 350.84 | 6.52 |
| TPH_29to36 | 20_30 | 4426.66 | 9.00 | 1480.00 | 15.81 |
| TPH_29to36 | 30_50 | 6683.76 | 9.00 | 1050.85 | 23.87 |
| TPH_29to36 | 50_75 | 2384.15 | 9.00 | 1080.94 | 8.51 |
| TPH_29to36 | 75_100 | 28.55 | 6.00 | 13.21 | 0.10 |
| TPH_37toUP | 00_10 | 699.96 | 9.00 | 202.90 | 2.50 |
| TPH_37toUP | 10_20 | 755.81 | 9.00 | 203.83 | 2.70 |
| TPH_37toUP | 20_30 | 1517.44 | 9.00 | 517.34 | 5.42 |
| TPH_37toUP | 30_50 | 1588.26 | 9.00 | 243.85 | 5.67 |
| TPH_37toUP | 50_75 | 553.58 | 9.00 | 224.21 | 1.98 |
| TPH_37toUP | 75_100 | 6.76 | 6.00 | 6.29 | 0.02 |
| Carbon type   | Mangrove Arrival Year | Stock (tonnes ha\(^{-1}\)) | n | SE  | Depth (m) |
|--------------|-----------------------|-----------------------------|---|-----|-----------|
| TPH below    | 1986                  | 41.6                        | 3 | 6.2 | 0.3–1     |
| TPH below    | 2002                  | 35.1                        | 3 | 15.7| 0.14–1    |
| TPH below    | 2006                  | 41.9                        | 3 | 14.3| 0.08–0.75 |
| TPH total    | 1986                  | 48.0                        | 3 | 7.6 | 0–1       |
| TPH total    | 2002                  | 37.3                        | 3 | 16.5| 0–1       |
| TPH total    | 2006                  | 42.7                        | 3 | 14.6| 0–0.75    |

Table S2 TPH stock (tonnes ha\(^{-1}\)) and TPH stock below the oil spill horizon at the three study sites.
Table S3. Effect of sediment depths (cm) on TPH (n=51, R² = 0.45) and PAH content (n=51, R²= 0.58). Bold font indicates significant difference in TPH and PAH content (P < 0.01).

| Depth (cm) | Total TPH (mg kg⁻¹) | Total PAH (mg kg⁻¹) |
|------------|---------------------|---------------------|
|            | Estimate            | SE                  | t       | p      | Estimate | SE       | t       | p      |
| [0-10 cm]  | 3834.8              | 3818.4              | 1.00    | 0.32   | 8.2      | 6.4      | 1.27    | 0.21   |
| (intercept) |                     |                     |         |        |          |          |         |        |
| [10-20 cm] | 1551.1              | 5400                | 0.29    | 0.78   | 5.7      | 9.1      | 0.63    | 0.54   |
| [20-30 cm] | 10979.8             | 5400                | 2.03    | 0.05   | 14.4     | 9.1      | 1.58    | 0.12   |
| [30-50 cm] | 26606.8             | 5400                | 4.93    | <0.01  | 61.7     | 9.1      | 6.79    | <0.01  |
| [50-75 cm] | 6646.2              | 5400                | 1.23    | 0.23   | 21.6     | 9.1      | 2.38    | 0.02   |
| [75-100 cm]| -3709.6             | 6037.4              | -0.61   | 0.54   | -0.7     | 10.2     | -0.06   | 0.95   |
Fig. S1 Timestamped satellite imagery of oil spill study area at Stony Creek, Victoria, Australia (as of 17/Jan/2020).
Fig. S2 Concentrations of TPH (Total TPH, TPH C₆₋₉, TPH C₁₀₋₁₄, TPH C₁₅₋₂₈, TPH C₂₉₋₃₆, TPH C₃₇₋₃₆) at six depth intervals (0-10, 10-20, 20-30, 30-50, 50-75 and 75-100 cm) across three sampling sites, Stony Creek, Australia. Site 3 was sampled till maximum 75 cm depth due to bedrock bottom.