Journal Pre-proof

Forest fires as drivers of contamination of polycyclic aromatic hydrocarbons to the terrestrial and aquatic ecosystems

Isabel Campos, Nelson Abrantes

PII: S2468-5844(21)00065-9

DOI: https://doi.org/10.1016/j.coesh.2021.100293

Reference: COESH 100293

To appear in: *Current Opinion in Environmental Science & Health*

Received Date: 10 April 2021

Revised Date: 11 July 2021

Accepted Date: 15 July 2021

Please cite this article as: Campos I, Abrantes N, Forest fires as drivers of contamination of polycyclic aromatic hydrocarbons to the terrestrial and aquatic ecosystems, *Current Opinion in Environmental Science & Health*, https://doi.org/10.1016/j.coesh.2021.100293.

Forest fires as drivers of contamination of polycyclic aromatic hydrocarbons to the terrestrial and aquatic ecosystems

Isabel Campos[1*] and Nelson Abrantes[1]

Centre for Environmental and Marine Studies (CESAM) and Department of Environment and Planning, University of Aveiro, Aveiro, Portugal

[*]Corresponding author: icampos@ua.pt

Keywords

Forest fires; PAHs; Soil; Water; Fate; Environmental pollution

Abstract

Forest fires are a well-known source of polycyclic aromatic hydrocarbons (PAHs), playing an important role on their formation and redistribution across the terrestrial and aquatic compartments. Fire-induced inputs of PAHs to the environment are of major concern due to their toxicity, high persistence and tendency to bioaccumulate. This paper presents a synthesis of the most important work on the role of wildfires and time since fire in the production and mobilization of PAHs on soil and water. Furthermore, it also assesses their toxic effects on aquatic species. The post-fire PAHs fluxes vary depending on a variety of factors, such as vegetation composition and plant's part burnt, fire severity and post-fire hydrological conditions. In general, off-site effects are particularly notorious during the initial post-fire period, although not necessarily limited to it. This review highlights the role of forest fires in the production and mobilization of PAHs, acting thus as a diffuse source of PAHs contamination to the terrestrial and aquatic systems, thus warning to the need to be considered in future monitoring/management programs on the environmental impacts of wildfires.

1. Introduction

Wildfires are recognized as a natural and beneficial phenomenon and even an important evolutionary driver of forest ecosystems playing an important role to keep and shape the ecosystem dynamics, promoting biodiversity and productivity [1,2]. However, under the changing climate conditions due to global warming and driven by human land-use change, the current and future wildfire regimes have been causing widespread concerns due to their socio-economic and environmental impacts such as loss of lives and properties, costs of suppression, and damages to ecosystems and the services they provide [3-5].

The major impacts of wildfires range from the on-site effects as the destruction of vegetation and organic matter, changes in soil structure, physical, chemical and biological properties and geomorphological and hydrological responses [6-11] to off-site effects as the contamination of fire-affected watersheds [12-16]. Arguably, the effects of the fire-induced production and mobilization of ubiquitous polycyclic aromatic hydrocarbons (PAHs) [17-23] assumes particular attention and raise environmental and biological concerns due to their toxic, mutagenic, carcinogenic and teratogenic potential, persistence within ecosystems and tendency to bioaccumulate [24-27]. For this reason, USEPA (US Environmental Protection Agency) has listed sixteen PAHs as priority pollutants: naphthalene (NAP), acenaphthylene (ACY), acenaphthene (ACE), fluorene (FLU), phenanthrene (PHE), anthracene (ANT), fluoranthene (FLT), pyrene (PYR), benzo(a)anthracene (BaA), chrysene (CHR), benzo(a)pyrene (BaP), benzo(b)fluoranthene (BbF), benzo(k)fluoranthene (BkF), indeno(1,2,3-cd)pyrene (IND), dibenzo(a,h)anthracene (DBA) and benzo(g,h,i)perylene (BGP). Naphthalene, ANT, FLT, BbF, BaP, IND and BghiP are also included in the list of priority substances of the European Commission [26]. Since PAHs produced during combustion in wildfires are emitted into the atmosphere, they can be redistributed between the vapor and particulate phases and are subsequently transported away over long distances and/or deposited to the terrestrial and aquatic environments, through dry or wet deposition [28] as well as mobilized between those compartments (Fig. 1). They can be deposit onto the soil surface, either directly by combustion of vegetation or mineralization of organic matter, or indirectly through interactions of ashes with the underlying soil, and by litter fall. Furthermore, they can be leached into soil profile or transported by overland flow, impacting surface and groundwater bodies. These post-fire pollutant fluxes will vary depending on a variety of factors such as soil type, topographic conditions of the terrain, vegetation composition, fire intensity, and post-fire climate conditions, such as timing, wind and intensity of precipitation events [8-10,14-15,17-19,21,39]. Although PAHs are strongly adsorbed to organic particles they can volatilize and degraded by abiotic and biotic processes [29]. Therefore, it is important to consider the risks of PAHs contamination posed by wildfire to the environment.

The present review tackles the role of wildfires as a potential source of PAHs contamination to the terrestrial and aquatic ecosystems, highlighting the current research on this topic.

Figure 1: Transport of polycyclic aromatic hydrocarbons (PAHs). (Modified from [58])

2. Effects of wildfires on the production and mobilization of PAHs in forest ecosystems

2.1. Wildfires impacts on the terrestrial ecosystems

An important consequence of wildfires with hydrological, geomorphological and ecological implications is the deposition of a layer of ash on the soil surface [30]. Although ash properties change according to the fire severity, type and part of burnt vegetation, temperature and time of contact a [30-32], they are mostly composed of oxides, hydroxides and carbonates; the main inorganic components are magnesium (Mg), silicon (Si), potassium (K) and calcium (Ca), and, to a lower extent by sodium (Na), phosphorous (P), sulphur (S), and other elements aluminum (Al), vanadium (V), chromium (Cr), manganese (Mn), iron (Fe), cobalt (Co), nickel (Ni), copper (Cu), zinc (Zn), arsenic (As), cadmium (Cd), mercury (Hg) and lead (Pb) [9,16,31,33-38]. In addition, wildfire ashes may also contain organic compounds, such as polycyclic aromatic hydrocarbons (PAHs) and occasionally polychlorinated dibenzodioxins, dibenzofurans (PCDD/Fs) and polychlorinated biphenyls (PCBs) [17-19, 34-35].

Worth stressing to this respect is that the ash layer is typically very prone to post-fire mobilization and export by wind and water, leading to the leaching of those compounds into the soil and groundwater as well as to their transport by overland flow to water bodies. Likewise, the presence of ash after a fire can have huge impacts on terrestrial and freshwater ecosystems [30-31].

Indeed, several authors [17-19, 34-35] reported significant amounts of the $\sum_{16}$ PAHs, ranging from 458 ngg^{-1} to 14078 ngg^{-1}, in wildfires ashes from different geographical regions, vegetation types and fire severity. After the 2017 Thomas Fire in southern California Wang et al. [34] reported levels of $\sum_{16}$PAHs in ashes from orchads between 2840 ngg^{-1} to 4450 ngg^{-1}. Campos et al. [18] in a study conducted in Portugal, in eucalypt and pine forest reported a temporal decrease 15 months after the fire on the $\sum_{15}$PAHs from 458 ngg^{-1} to 275 ngg^{-1} and from 695 ngg^{-1} to 285 ngg^{-1}, respectively. A similar trend (from 11007 ngg^{-1} to 1169 ngg^{-1}) was reported by Simon et al [17] in the levels of $\sum_{16}$PAHs in ash from pine forest collected in South Korea 19 and 492 days after the forest fire. In a study conducted by Harper et al. [36] in ashes from six wildfires types [different species, fire severities and countries: Australia (AUS), United Sates of America, Canada, Spain and United Kingdom (UK)] found significant variations in the concentration of $\sum_{16}$PAHs, ranging from 1155 to 14078 ngg^{-1}, the highest total being found in the moderate severity fire in the UK and the lowest in the moderate to high severity fire in the AUS. Campos et al [18] also found that ash contents showed a clear tendency to be lower (eucalypt: 315 ngg^{-1}; pine: 429 ngg^{-1}) following a high severity fire than following a moderate

severity fire (eucalypt: 458 ngg^{-1}; pine: 695 ngg^{-1}). Fire severity seems to play some role in the total ash PAHs concentrations. Important to note that in, general, ashes were dominated by of 2-3 ring (NAP, PHE, FLU, ACY) PAHs followed by 4-ring (FLT, PYR) [17-19,35]. In contrast, Wan et al. [34] found a considerable amount of higher ringed PAHs (≥ 4 rings) which can be due to the combustion of irrigation pipes in orchards.

The incorporation of ash into the soil profile has been referred in many studies as the main cause of changes in soil physical and chemistry properties [18,30,34]. Indeed, increases in PAHs in soils after ash deposition have been reported in several studies [18,21,34,39,40].

Despite wildfires being identified as a major source of PAHs, with the smoke of biomass burning revealing high PAH levels [28,41], their recognition as a source of diffuse contamination to terrestrial ecosystems has received less attention [17,18,20,21,34,39,42,43]. Overall, the former studies suggest that wildfires leads to the deposition of PAHs on the soil surface, bounded to ash and charcoal particles, and in an increase of PAHs contents of the topsoil, bound to soil organic matter. Indeed, PAHs concentrations in burnt soil immediately after the fire were markedly higher than unburnt soil concentrations, as reported by Tsibart et al. [42] and Abakumov et al. [43] in soils of drained peatlands in Moscow, Russia and sandy podzol soils of Nadym, Russia, respectively. Campos et al. [18] in a study conducted in eucalypt forest in Portugal and Choi [40] in a pine forest in South Korea, also reported enrichment in burnt soils of approximately 5 times relatively to the unburnt soils 1 month after the fire. Chen et al. [39] assessed that the levels of PAHs of unburnt soil (247±58 ngg^{-1}) < white ash/burnt soil (515±333 ngg^{-1}) < black ash/burnt soil (893±285 ngg^{-1}). In line with the former authors, Campo et al. [20] and Rey-Salgueiro et al. [21] in studies conducted in recently burnt forests in Spain also reported increased levels of PAHs in burnt soils compared to unburnt sites. The implied substantial wildfire-increased in PAHs contents is supported by the formation of PAHs by combustion of plant biomass during wildfires [44,45]. Possibly, the PAHs of the topsoil originated, at least in part, from the ash layer, itself. Namely, PAHs concentrations on ashes immediately after the fire (as described early) were markedly higher than topsoil concentration [17,18,34,39]. For example, Campos et al. [18] reported values of ∑PAHs: 458 vs. 148 ngg^{-1} (eucalypt) and 695 vs. 242 ngg^{-1} (pine), for ashes and burnt topsoil, respectively, while Simon et al. [17] found values of 11007 vs. 294 ngg^{-1}, respectively. In contrast, Simon et al. [17] and Wan et al. [34] reported similar values between the unburnt and burnt soils. However, with time since fire (especially after the first rainfalls), PAHs contents tend to decrease especially due to soil erosion by wind and water, and by leaching from the ash layer into the soil and to the groundwater as well as the vaporization and degradation of 2-3 ring PAHs [17,18,40]. As in the case of ashes, fire severity can influence the levels of PAHs in burnt

soils. For instance, in the study conducted by Campos et al. [18] values tended to be lower after a high severity fire than after a moderate severity fire, both in the case of eucalypts sites (-10%) and of the pines sites (-30%). Chen et al. [39] also reported the same trend.

Similar to the ash profile, burnt soils were characterize by the dominance of 2-4 ring PAHs (NAP, PHE, FLU, FLT and PYR) [17,18,20,21,39,40], which is in accordance with the most produced aromatic compounds during wildfires [28,41] and by pinewood and needles combustion [45]. For example, Campos et al. [18] observed a temporal decreased (from 69% to 44% over the first 4 months) in the contribution of the 3-ring PAHs mainly PHE and FLU) to the total PAHs while the 4-ring (FLT) increased. In general, this pattern was in line with other authors, who also reported a decreasing trend in the fraction of 2-3 rings PAHs (NAP, PHE) and an increase in the fraction of 4-ring PAHs over time [17,40].

In spite of this decrease with time since fire, post-fire PAHs loads can pose a long/term threat to the environment implying a degradation of the land. Clearly, the results from the former studies consistently indicate that forest fires can be a significant non-point diffuse source of PAHs to the terrestrial systems.

2.2. Wildfires impacts on the aquatic ecosystems

The risks of post-fire contamination are not limited to the burnt soils but can also affect surface and groundwater bodies within and downstream of the burnt area. Transport of PAHs from soil to water by surface runoff, either in dissolved or particulate form is likely to be significant in recently burnt areas, as fire typically enhances overland flow generation and the associated transport of ash and soil particles to downstream surface water bodies [10,12-16], impacting their water quality [22,45-51]. Furthermore, PAHs deposited in the bottom sediments of water bodies can resuspending periodically, leading to lasting water quality issues [52]. These contaminants can also be leached into the soil profile impacting groundwater [22,53,54].

In the surface water, PAHs can volatilize, photodegrade, oxidize, biodegrade by aquatic organism, bind to particulates or accumulate in aquatic organisms (see Fig.1), depending on their physicochemical properties. Because of their low solubility and high affinity for organic carbon, PAHs in aquatic systems are primarily found sorbed to particles that either settles to the bottom or as suspended in the water column [56]. In sediments, PAHs can biodegrade or accumulated in benthic organisms [56].

Although the importance of considering the impacts of the inputs of PAHs to freshwater systems, only few studies have been addressing this issue. Olivella et al. [46] and Vila-Escalé et al. [47] observed an increased in post-fire inputs of PAHs to streams one month after a fire in

Catalonia, Spain, although, in the first case was attributed to atmospheric deposition of ashes (in absence or low rain after the fire) and in the second, to post-fire erosion. In both studies, the 3-ring (PHE) and 4-ring (PYR) were the dominant PAHs in water samples. Furthermore, the total concentrations of the PAHs decreased with time since fire, approaching the background levels. Worth stressing is that the concentrations of PAHs measured remain within the European drinking water limits and never reached levels of toxicological concern. In line with the previous studies, Schäfer et al. [49] monitored the levels of PAHs in 9 streams in Victoria, Australia following a wildfire and found that compounds with 3-ring PHE and FLU) and 4-ring (PYR) were the predominant (levels of PAHs ranged from 0.1 to 9 ngL^{-1}). In a study conducted by Stein et al. [48] in Southern California it was observed that the PAHs flux was 4 times greater from burned areas than from adjacent unburnt areas.

A study conducted by Mansilha et al. [22] in Caramulo Mountain, Portugal during 19 months, showed increases of 1.2-4.0 times higher than in the unburnt control samples, with the 2-ring (NAP) and 5-6 ring (BbF, BaP, BkF, BghiP and IND) as the most detected PAHs. The decay process of PAHs with time since fire was also observed in this study getting closer to the ones of the control samples by the end of the first year. Mansilha et al. [22,53,54] also determine the influence of wildfires on PAHs levels in groundwaters in Estrela and Gerês Mountains and Braga, in Portugal and found increases of 1-to 6-fold higher in systems within the burnt area than in the control sites, and a temporal reduction over time after intense precipitation conditions. These studies corroborate that wildfires can affect water quality and can threaten downstream drinking water supplies. Despite this, the detrimental impacts of the post-fire inputs of PAHs to the freshwater communities have been vaguely explored.

First steps to overcome this research gap were given by Campos et al. [50] and Vera et al. [35], whose studies demonstrate that PAHs released or mobilized by wildfires were capable of exerting significant toxicity to the bacteria *Vibrio fischeri*, the microalgae *Raphidocelis subcapitata* and the macrophyte *Lemna minor*. By contrast, no significant effects were found towards the cladoceran *Daphnia magna*. In contrast, Harper et al. [19] found effects on the immobilisation of *D. magna* when exposed to 3 of the 6 ash types. Furthermore, Nunes et al. [51] used a biomarker approach to find early warning signs of toxicity triggered by the exposure of the fish *Gambusia holbrooki* to aqueous runoff and stream water collected from a burnt catchment in Portugal. Pro-oxidative modifications involved in glutathione metabolism were the most relevant deleterious effects found, while no signs of neurotoxicity were observed. More recently, and in the same water samples as Nunes et al. [51], Carvalho et al. [56] showed the adverse effects on microbial communities and invertebrates in stream detrital food webs and they observed that the chemical composition and source of runoff explained

the different effects observed. In this overall context, Pradhan et al. [57] investigated the leaf consumption behaviour and the responses of oxidative and neuronal stress enzymatic biomarkers in the freshwater invertebrate shredder *Allogamus ligonifer*, after short-term exposure. The shredding activity was severely inhibited, and the enzymatic activity suggested oxidative and neuronal stress in the shredders upon exposure to post-wildfire runoffs. These results suggest that post-fire contamination can induce sublethal effects on invertebrate shredders with impacts on key ecological processes in streams.

All the reported findings, appear to justify concerns around the impacts of wildfires inputs of PAHs on water quality and aquatic biota, emphasizing the need to better understand their potential toxicity.

Final Remarks and Conclusions

It has been unequivocally demonstrated that forest fires are important non-point diffuse source of PAHs to the terrestrial and aquatic ecosystems as well as their numerous ecotoxicological effects over multiple aquatic organisms. However, despite the recognized risks that the ubiquity of PAHs in the forest ecosystems poses not only to the environment (soil and water ecosystems), but potentially also to human health, several research gaps remain in understanding their terrestrial and aquatic impacts.

A major challenge is to understand the transport and fate of PAHs in forest ecosystems and accordingly, which mechanisms are in stake. Fire induced PAHs loads can affect soil quality, fertility and productivity, especially when wildfires occur with a frequency or severity outside of the historic range of variation. Due to the persistence of PAHs in the environment, they can pose a long-term threat, which may lead to severe damage and land degradation that may not be identified until it is well advanced. This way, long-term studies are critical to better understand the delayed and persistent effects of fire on PAHs fate and mobilization in the terrestrial compartment. Furthermore, there is often a lack of connection between PAHs delivery from the land surface and within stream transport processes. This is of major concern, since contamination with PAHs represents a serious threat when they are transported and reach the aquatic systems such as rivers and water supplies reservoirs. In this regard, it is important to assess the fate and the medium- to long- term impacts of PAHs in the quality of waterbodies, mainly due to the problem associated with the resuspension of sediments as well as to assess the effectiveness of post-fire management techniques in mitigating post-fire PAHs.

Notwithstanding, for an adequate assessment, monitoring and predicting of the fire-induced pollution risks, it is necessary to increase the knowledge on the impacts of post-fire PAHs on the terrestrial and aquatic systems under several possible risk scenarios.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the project AQUAFIRE (PTDC/CTA-AMB/28936/2017) funded by FEDER, through COMPETE2020 (POCI) and by National funds (OE) through the Portuguese Foundation for Science and Technology (FCT/MCTES). Thanks are also due to FCT/MCTES for the financial support to CESAM (UIDP/50017/2020+UIDB/50017/2020), through National funds.

References

Papers of particular interest, published within the period of review, have been highlighted as:

* of special interest

* * of outstanding interest

1. Doerr SH, Santín C: **Global trends in wildfire and its impacts: perceptions versus realities in a changing world**. *Philosophical Transactions of the Royal Society B: Biological Sciences* 2016, **371**: 20150345.

2. Pausas JG, Keeley JE: **Wildfires as an ecosystem service**. *Frontiers in Ecology and the Environment* 2019, 17: 289-295.

3. Santín C, Doerr SH: **Fire effects on soils: the human dimension**. *Philosophical Transactions of the Royal Society B: Biological Sciences* 2016, **371**: 20150171.

4. IPCC (Intergovernmental Panel on Climate Change): *Climate Change 2013: The Physical Science Basis*. 2013. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

5. Moritz MA, Batllori E, Bradstock RA, Handmer J, Hessburg PF, Leonard J, McCaffrey S, Odion DC, Schoennagel T, Syphard AD: **Learning to coexist with wildfire**. *Nature* 2014, **515**: 58–66.

6. Foster CN, Barton PS, Robinson NM, MacGregor CI, Lindenmayer DB: **Effects of a large wildfire on vegetation structure in a variable fire mosaic**. *Ecological Applications* 2017, **27(8)**: 2369-2381.

7. Santín C, Doerr SH, Preston CM, González-Rodríguez G: **Pyrogenic organic matter production from wildfires: a missing sink in the global carbon cycle**. *Global Change Biology* 2016, **22**: 76-91.

8. Certini G: **Effects of fire on properties of forest soils: a review**. *Oecologia* 2005, **143**: 1-10.

9. Campos I, Abrantes N, Keizer JJ, Vale C, Pereira P: **Major and Trace Elements in Soils and Ashes of Eucalypt and Pine Forest Plantations in Portugal Following a Wildfire**. *Science of the Total Environment* 2016, **572**: 1363-1376.

10. Vieira DCSA, Malvar MCA, Fernández CB, Serpa DA, Keizer JJ: **Annual runoff and erosion in a recently burn Mediterranean forest – the effects of plowing and time since fire**. *Geomorphology* 2016, **270**: 172–183.

11. Girona-García A. Silva J, Fernández C, Robichaud R, Keizer JJ: **Effectiveness of post-fire soil erosion mitigation treatments: A systematic review and meta-analysis**. *Earth-Science Reviews* 2021, **217**: 103611.

12. Hahn GE, Coates A, Latham RE, Majidzadeh H: **Prescribed fire effects on water quality and freshwater ecosystems in moist temperate Eastern North America**. *Natural Areas Journal* 2019, **39(1)**: 46-57.

13. Rust AJ, Hogue TS, Saxe S, McCray J: **Post-fire water-quality response in the western United States**. *International Journal of Wildland Fire* 2018, **27(3)**: 203-216.

14. Abraham J, Dowling K, Florentine S: **Risk of post-fire metal mobilization into surface water resources: A review**. *Science of the Total Environment* 2017, **599-600**: 1740-1755.

15.* Nunes JP, Doerr SH, Sheridan G, Neris J, Santín C, Emelko MB, Silins U, Robichaud PR, Elliot WJ, Keizer JJ**: Assessing water contamination risk from vegetation fires: challenges, opportunities and a framework for progress**. *Hydrological Processes* 2017, **32**: 687-694.

This work provides an interesting analysis about the challenges for assessing water contamination risk from wildfires

16. Yu M, Bishop TFA, Van Ogtrop FF: **Assessment of the decadal impact of wildfire on water quality in forested catchments**. *Water*, 2019, *11*:533.

17.** Simon E, Choi S-D, Park M-K: **Understanding the Fate of Polycyclic Aromatic Hydrocarbons at a Forest Fire Site Using a Conceptual Model Based on Field Monitoring**. *Journal of Hazardous Materials* 2016, **317**: 632–39.

In this work authors carry out an excellent assessment of the temporal evolution of PAHs levels in soils after a wildfire and its relation with the ash-bed structure and precipitation regime. Furthermore, they applied a model to explain the most relevant processes affecting the fate of PAHs after a wildfire.

18.** Campos I, Abrantes N, Pereira P, Micaelo AC, Keizer JJ: **Forest fires as potential triggers for production and mobilization of polycyclic aromatic hydrocarbons to the terrestrial ecosystem**. *Land Degradation & Development* 2019, **30(18)**: 2360-2370.

This work makes a very comprehensive study about the impacts of wildfires on forest soils by addressing both the direct and indirect fire effects by studying not only the PAHs levels on the topsoil but also on the ash layer during 15 months. Furthermore, it also addressed the influence of different forest management and contrasting fire severities.

19.** Harper AR, Santín C, Doerr SH, Froyd CA, Albini D, Otero XL, Viñas L, Pérez-Fernandez B: **Chemical composition of wildfire ash produced in contrasting ecosystems and its toxicity to *Daphnia magna***. *International Journal of Wildland Fire* 2019, **28**: 726-737.

In this paper the authors presents for the first time an ecotoxicological assessment with one aquatic species allowing the direct comparison between the composition and toxicity of ash from worldwide contrasting ecosystems (Australian, USA, Canadian, Spanish and UK).

20. Campo J, Lorenzo M, Cammeraat LH, Picó Y, Andreu V: **Emerging contaminants related to the occurrence of forest fires in Spanish Mediterranean**. *Science of the Total Environment* 2017, **603-604**: 330-339.

21.* Rey-Salgueiro L, Martinez-Carballo E, Merino A, Vega JA, Fonturbel MT, Simal-Gandara J: **Polycyclic aromatic hydrocarbons in soils organic horizons depending on the soil burn severity and type of ecosystem**. *Land Degradation & Development* 2018, **29**: 2112-2123.

The authors did a very good work about the effects of fire severity and type of ecosystem on polycyclic aromatic hydrocarbons inputs to the forest soils

22.** Mansilha C, Duarte CG, Melo A, Ribeiro J, Flores D, Espinha Marques J: **Impact of wildfires on water quality in Caramulo Mountain ridge (Central Portugal)** Sustainable Water

Resources Management 2017, **5**: 319-331.

This work is of special interest because it assess the short- to medium post-fire impacts on groundwater and surface water in a forest catchment that is also used for the supply of potable water.

23. Sampei Y, Uraoka S, Ono T, Dettman: **Polycyclic aromatic hydrocarbons (PAHs) in sediment cores from lakes Shinji and Nakaumi, SW Japan: a proxy of recent fire events in the watershed**. *Estuarine, Coastal and Shelf Science* 2019, **226**: 1-7.

24. ATSDR (Agency for Toxic Substances and Disease Registry): *Toxicological profile for polycyclic aromatic hydrocarbons*. 1995. U.S. Department of Health and Human Services, Public Health Service, Atlanta, GA. https://www.atsdr.cdc.gov/toxprofiles/tp69.pdf

25. IARC (International Agency for Research on Cancer): *IARC monographs on the evaluation of carcinogenic risk of chemicals to human. Non-heterocyclic polycyclic aromatic hydrocarbons and some related exposure*. 2010. Volume 92. World Health Organization, Lyon, France.

26. European Commission (EC): *Commission Regulation No. 1881/2006 of 19 December 2006 setting maximum levels for certain contaminants in foodstuff*. 2006. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32006R1881

27. Wallace SJ, Solla SR, Head JA, Hodson PV, Parrott JL, Thomas PJ, Berthiaume A, Langlois VS: **Polycyclic aromatic compounds (PACs) in the Canadian environment: exposure and effects on wildlife**. *Environmental Pollution* 2020, **265**: 114863.

28. Luo J, Han Y, Zhao Y, Huang Y, Liu X, Tao S, Liu J, Huang T, Wang L, Chen K, Ma J: **Effect of northern boreal forest fires on PAH fluctuations across the arctic**. *Environmental Pollution* 2020, **261**: 114186.

29. Lawal AT: **Polycyclic aromatic hydrocarbons. A review**. *Cogent Environmental Science* 2017, 3(1): 1339841.

30. Bodí MB, Martin DA, Balfour VN, Santín C, Doerr SH, Pereira P, Cerdà A, Mataix-Solera J: **Wildland fire ash: Production, composition and eco-hydro-geomorphic effects**. *Earth-Science Reviews* 2014, **130**: 103-127.

31. Santín C, Doerr SH, Otero XL, Chafer CJ: **Quantity, composition and water contamination potential of ash produced under different wildfire severities**. *Environmental Research* 2015, **142**: 297–308.

32. Brook A, Wittenberg L: **Ash-soil interface: Mineralogical composition and physical**

structure. *Science of the Total Environment* 2016, **572**: 1403-1413.

33. Campos I, Vale C, Abrantes N, Keizer JJ, Pereira P: **Effects of Wildfire on Mercury Mobilisation in Eucalypt and Pine Forests**. *Catena* 2015, **131**: 149–59.

34. Wan X, Li C, Parikh SJ: **Chemical composition of soil-associated ash from the southern California Thomas fire and its potential inhalation risks to farmworkers**.: *Journal of Environmental Management* 2021, **278**: 1-10.

35. Silva V, Pereira JL, Campos I, Keizer JJ, Gonçalves F, Abrantes N: **Toxicity assessment of aqueous extracts of ash from wildland fires**. *Catena* 2015, **135**: 401–408.

36. Brito DQ, Passos CJS, Muniz DHF, Oliveira-Filho EC: **Aquatic ecotoxicity of ashes from Brazilian savanna wildfires**. *Environmental Science Pollution Research* 2017, **24**: 19671-19682.

37. Oliveira-Filho EC, Brito DQ, Dias ZMB, Guarieiro MS, Carvalho EL, Fascineli ML, Niva CC, Grisolia CK: **Effects of ashes from a Brazilian savanna wildfire on water, soil and biota: An ecotoxicological approach**. *Science of the Total Environment* 2018, **618**: 101-111.

38. Brito DQ. Santos LHG, Passos CJS, Oliveira-Filho EC: **Short‐Term Effects of Wildfire Ash on Water Quality Parameters: A Laboratory Approach**. *Bulletin of Environmental Contamination and Toxicology* 2021, https://doi.org/10.1007/s00128-021-03220-9.

39. Chen H, Chow AT, Li XW, Ni HGDahlgren RA, Zeng H, Wang JJ: **Wildfire Burn Intensity Affects the Quantity and Speciation of Polycyclic Aromatic Hydrocarbons in Soils**. *ACS Earth and Space Chemistry* 2018, **2(12)**: 1262-1270.

40. Choi S-D: **Time trends in the levels and patterns of polycyclic aromatic hydrocarbons (PAH's) in pine bark, litter, and soil after a forest fire**. *Science of the Total Environment* 2014, **470-471**: 1441-1449.

41. Vicente A, Calvo A, Fernandes AP, Nunes T, Monteiro C, Pio C, Alves C: **Hydrocarbons in particulate samples from wildfire events in central Portugal in summer 2010**. *Journal of Environmental Sciences* 2017, **53**: 122-131.

42. Tsibart A, Gennadiev A, Koshovskii T, Watts A: **Polycyclic aromatic hydrocarbons in post-fire soils of drained peatlands in western Meshchera (Moscow region, Russia)**. *Solid Earth* 2014, **5**: 1305-1317.

43. Abakumov E, Pechkin A, Chebykina E, Shamilishvili G: **Effect of the Wildfires on Sandy Podzol Soils of Nadym Region, Yamalo-Nenets Autonomous District, Russia**. *Applied and Environmental Soil Science* 2020, **2020**: 8846005.

394 44. Samburova V, Connolly J, Gyawali M, Yatavelli RLN, Watts AC, Chakrabarty RK, Zielinska B,
395 Moosmüller H, Khlystov A: **Polycyclic aromatic hydrocarbons in biomass-burning emissions**
396 **and their contribution to light absorption and aerosol toxicity**. *Science of the Total*
397 *Environment* 2016, **568**: 391-401.

398 45. Conde JC, Ayla JH, Afonso AM, Gonzalez V: **Emissions of polycyclic aromatic hydrocarbons**
399 **from combustion of agricultural and sivilcultural debris**. *Atmospheric Environment* 2005, **39**:
400 6654-6663.

401 This work provides an interesting analysis about the challenges for assessing water
402 contamination risk from wildfires

403 46. Olivella MA, Ribalta TG, Febrer AR, Mollet JM, Heras FXC: **Distribution of polycyclic**
404 **aromatic hydrocarbons in riverine waters after Mediterranean wildland fires**. *Science of the*
405 *Total Environment* 2006, **355**: 156-166.

406 47. Vila-Escalé M, Vegas-Vilarrúbia T, Prat N: **Release of polycyclic aromatic compounds into a**
407 **Mediterranean creek (Catalonia, NE Spain) after a forest fire**. *Water Research* 2007, **41**: 2171-
408 2179.

409 48. Stein ED, Brown JS, Hogue TS, Burke MP, Kinoshita A: **Stormwater contaminant loading**
410 **following Southern California wildfires**. *Environmental Toxicology and Chemistry* 2012, **33(11)**:
411 2625-2638.

412 49. Schäfer RB, Hearn L, Kefford BJ, Mueller JF, Nugegoda D: **Using silicone passive samplers**
413 **to detect polycyclic aromatic hydrocarbons from wildfires in streams and potential acute**
414 **effects for invertebrate communities**. *Water Research* 2010, **22**: 4590-4600.

415 50.** Campos I, Abrantes N, Vidal T, Bastos AC, Gonçalves F, Keizer JJ: **Assessment of the**
416 **Toxicity of Ash-Loaded Runoff from a Recently Burnt Eucalypt Plantation**. *European Journal*
417 *of Forest Research* 2012, **131 (6)**: 1889–1903.

418 This paper report for the first time the toxic effects of post-fire PAHs on aquatic species
419 emphasizing the role of wildfires as potential source of PAHs to waterbodies.

420 51. *Nunes B, Silva V, Campos I, Pereira JL, Pereira P, Keizer JJ, Gonçalves F, Abrantes N: **Off-**
421 **site impacts of wildfires on aquatic systems — Biomarker responses of the mosquitofish**
422 ***Gambusia holbrooki***. *Science of the Total Environment* 2017, **581**:305–313.

423 This paper report for the first time the biochemical effects of post-fire PAHs on fish *Gambusia*
424 *holbrooki* emphasizing the role of wildfires as potential source of PAHs to waterbodies.

52. Sampei Y, Uraoka S, Ono T, Dettman: **Polycyclic aromatic hydrocarbons (PAHs) in sediment cores from lakes Shinji and Nakaumi, SW Japan: a proxy of recent fire events in the watershed**. *Estuarine, Coastal and Shelf Science* 2019, **226**: 1-7.

53. Mansilha C, Carvalho A, Guimarães P, Espinha Marques J: **Water quality concerns due to wildland fires: polycyclic aromatic hydrocarbons (PAH) contamination of groundwaters mountain areas**. *Journal of Toxicology and Environmental Health, Part A: Current Issues* 2015, **77**: 806-815.

54. Mansilha C, Melo A, Martins ZE, Ferreira IMPLVO, Pereira AM, Espinha Marques J: **Wildfires effects on groundwater quality from springs connected to small public supply systems in a peri-urban forest area (Braga Region, NW Portugal)**. *Water* 2020, **12, 1146**: 1-16.

55. Yu M-H: *Environmental toxicology: biological and health effects of pollutants*. 2005. 2nd edition, CRC Press, Boca Raton.

56. Carvalho F, Pradhan A, Abrantes N, Campos I, Keizer JJ, Cassio F, Pascoal C: **Wildfire impacts on freshwater detrital food webs depend on runoff load, exposure time and burnt forest type**. *Science of the Total Environment* 2019, **692**: 691-700.

57. Pradhan A, Carvalho F, Abrantes N, Campos I, Keizer JJ, Cassio F, Pascoal C: **Biochemical and functional responses of stream invertebrate shredders to post-wildfire contamination**. *Environmental Pollution* 2020, **267**: 115433.

58. Campos I, Abrantes N, Pereira P, Keizer JJ, 2018: Polycyclic aromatic hydrocarbons. In Fire effects on soils. State of the art and methods used. Edited by Pereira P, Mataix-Solera J, Úbeda X, Rein G, Cerdà A. CSIRO Publishers, 2018:

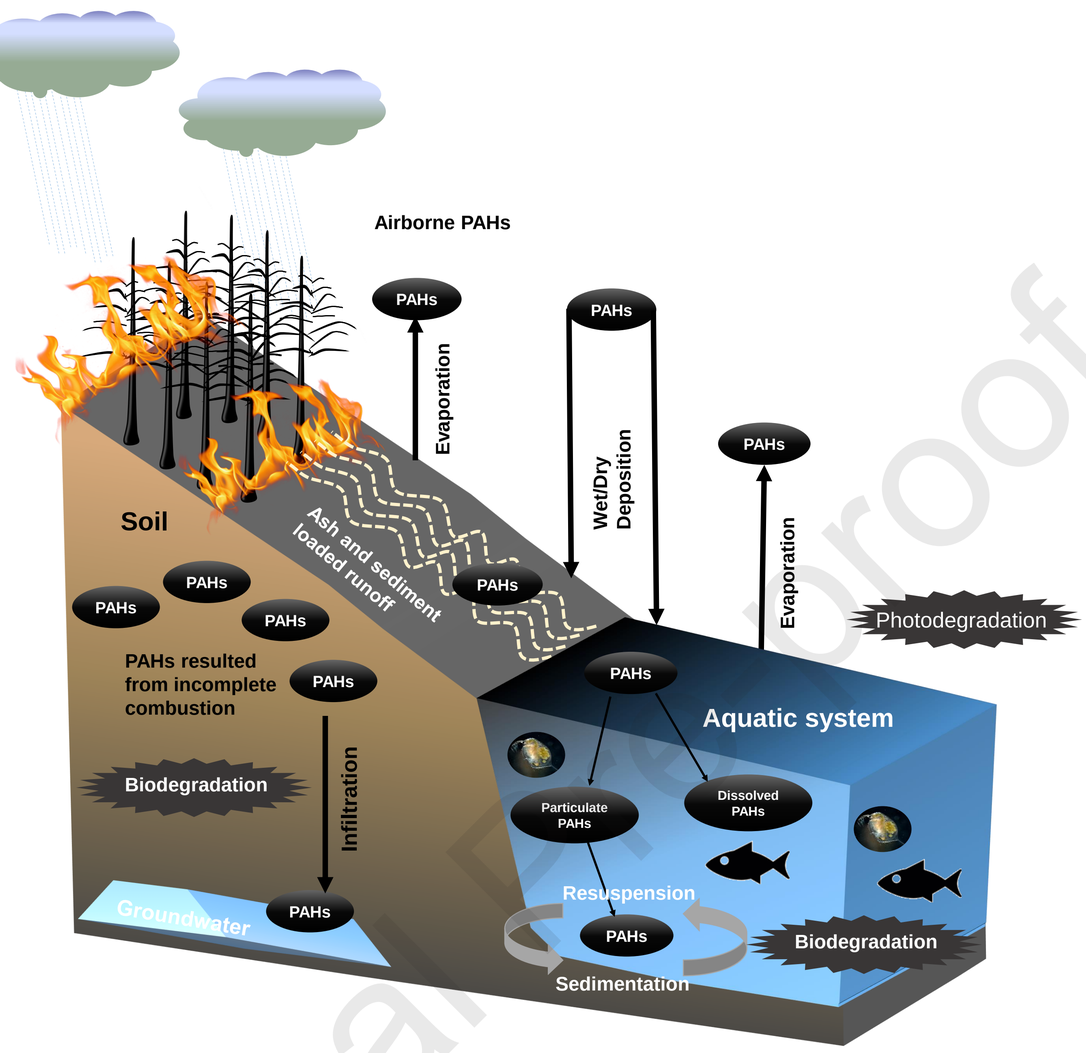

Figure 1: Transport of polycyclic aromatic hydrocarbons (PAHs). (Modified from [58])

Declaration of interests

x The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.