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# Fire and water: global fire impacts on physicochemical properties of freshwater ecosystems

**Jenny J. Morales**
Universidade Federal de Mato Grosso
**Nayara D. S. Paes**
Universidade Federal de Mato Grosso
**Andressa C. M. Silva**
Universidade Federal de Mato Grosso
**Alberto L Teixido**
Universidade Federal de Mato Grosso https://orcid.org/0000-0001-8009-1237

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# Abstract

Freshwater ecosystems are intensely endangered, entailing declines in the biodiversity and ecosystem services. Fire may affect physicochemical water quality parameters of these environments by transference of ash and toxic substances into water bodies, altering nutrient and oxygen concentrations, temperature or turbidity. However, major knowledge gaps in the impacts of fire on freshwater habitats are prevalent. We conducted a global systematic review by searching articles in the Web of Science related to the impacts of fire on the physicochemical water properties of freshwater ecosystems. We estimated ecological and geographic biases, quantified the set of physicochemical parameters investigated, and provided an overview of fire-mediated alterations. We found 54 articles published between 1976 and 2019, with a significant increase during the last decade. Research was strongly biased towards a few western countries, mostly across North America, Europe and Australia. Lotic systems were considerably more studied than lentic systems. Overall, 57 chemical and 17 physical parameters were evaluated, comprising 304 and 77 cases, respectively. Fire altered 68% of the cases studied and this alteration was proportionally similar between chemical (66%) and physical (75%) properties. Nutrient concentration, metal ions, alkalinity, turbidity and temperature were recurrently increased parameters by fire, whereas oxygen mostly decreased. Our study demonstrates that fire commonly affects water quality parameters of freshwater ecosystems. Biases and resulting gaps may steer future sampling efforts and promote a broader understanding of the impacts of fire on these environments. Our results may ultimately guide applicable conservation policies for biodiversity and water management strategies of freshwater habitats.


# Introduction

Fire causes large disruptions and changes in the diversity, functioning and services of many ecosystems (Kelly et al. 2020; Shakesby and Doerr 2006). Burning of vegetation has become increasingly more frequent, intense and severe in recent decades (Halofsky et al. 2020; Jolly et al. 2015; Pausas and Keeley 2009; but see Andela et al. 2017 for savannas and grasslands). While the effects of fire are broadly studied across different terrestrial ecosystems worldwide (Pausas and Ribeiro 2017), their effects on aquatic ecosystems are relatively less known (Bixby et al. 2015). However, the disturbance of vegetation and soil structure related to fire may severely alter the local microclimate, the hydrological processes and water quality of aquatic environments (e.g., Gustine et al., 2021; Pettit and Naiman 2007; Smith et al. 2011; Townsend and Douglas 2004). Ultimately, fire-induced impacts on aquatic habitats may produce major perturbation on their biodiversity, dynamic and structure (Bixby et al. 2015).

Continental aquatic ecosystems (i.e., freshwater ecosystems) are among the most diverse ecological communities worldwide and provide essential services to human societies, yet they are intensely endangered environments with an increased loss of biodiversity and ecosystem services (e.g., Baggio et al. 2021; Dudgeon et al. 2006; Harrison et al. 2018; Reid et al. 2019; Vörösmarty et al. 2010). However, major knowledge gaps in biodiversity and ecosystem functioning of freshwater environments are noticeable, because of a strong bias toward marine and terrestrial ecosystems in biological samplings and conservation research (Barros et al. 2020; Carrizo et al. 2017; Clark and May 2002; Darwall et al. 2011). Determining sampling biases and knowledge gaps in fire-related research of these vulnerable aquatic habitats is crucial to steer future research efforts and provide suitable conservation policies.

In freshwater ecosystems, fires cause direct effects by reducing surrounding (e.g., riparian forest) or interspersed (e.g., wetland) vegetation, and altering biological and physicochemical soil properties. Bordering soil and vegetation provide essential ecosystem functions to freshwater habitats, buffering nutrient discharge, avoiding excessive erosion and sedimentation, and subsequently preventing the entry of waste and allochthonous material (Boerner et al. 2009; Lathrop 1994; Pereira et al. 2019; Townsend and Douglas 2004). Fire-driven soil and vegetation alteration may thus cause indirect effects on freshwater ecosystems. Indirect effects are mostly related to changes in the local microclimate and the transfer of ash and toxic substances into water bodies, inducing shifts in the physicochemical characteristics of water (i.e., water quality parameters), such as increased nutrients, sediments, temperature, turbidity, alkalinity and electrical conductivity, or a decrease, for example, in dissolved oxygen (Belillas and Rodà 1993; Brito et al. 2021; Carignan and Lamontagne 2000; Hitt 2003; Hohner et al. 2016; Smith et al. 2011). These changes can ultimately stimulate the proliferation of primary producers such as phytoplankton, periphyton and macrophytes, promoting the eutrophication of freshwater ecosystems, that in turn affects water quality and biological integrity (Carignan and Lamontagne 2000; Monaghan et al. 2019; Oliver et al. 2012; Rhea et al. 2021). Altogether, fire-related hydrological changes can lead to the mortality of aquatic biota, including plant communities, plankton, macroinvertebrates and fishes (Carvalho et al. 2019; Hitt 2003; Silva et al. 2015). Likewise, such changes may entail major restrictions on water availability and demand for agricultural, domestic and industrial purposes (Baggio et al. 2021; Emelko et al. 2011; Hallema et al. 2018). Understanding the effect of fire on water quality parameters in freshwater ecosystems can help to guide more targeted and applicable conservation actions on these vulnerable environments, their associated biodiversity, and water needs for humans.

In this study, we aim to provide a comprehensive and critical global systematic review related to the effect of fire on water quality in freshwater ecosystems. We considered fires in a broad sense, including wildfires (i.e., natural and human-sparked) and controlled fires (i.e., prescribed and experimental). To do this, we conducted an exhaustive literature review of the publications about this topic. Physical and chemical water parameters may be differentially affected by fire and generate diverse impacts on aquatic biota (Bixby et al. 2015; Rust et al. 2019; Smith et al. 2011). Consequently, the identification of gaps and the variation in the response of water quality parameters to fire are also crucial to provide useful information to better support conservation decisions. Specifically, our objectives were to: (1) estimate biases and gaps in the ecological and geographic patterns of water quality parameters investigated; and (2) provide an overview of the impact of fire on the physical and chemical parameters of water quality.

# Materials And Methods

### Data source and collection

We searched the articles evaluating the effects of fire on water quality parameters of freshwater ecosystems in the Web of Science database (ISI Web of Knowledge – http://apps.webofknowledge.com; hereafter, WOS) on 26 November 2019. Our survey included high-sensitivity and low-specificity terms (see Pullin and Stewart 2006) related to this topic. Thus, we searched for ("water quality" OR “water component*” OR “water parameter*” OR “water propert*”) AND (*fire* OR soot* OR ash* OR smoke* OR burn* OR combustion*) AND (freshwater OR “aquatic ecosystem*”) anywhere in the full record by using the “All fields” (ALL) field tag. We considered all articles provided at the time of the survey (most recent papers from December 2019).

Our review exclusively focused on studies related to the effect of fire on water quality parameters (1) in freshwater ecosystems as study area, (2) considering natural, human-started, prescribed or experimental fires, (3) published in scientific articles, and (4) reporting the effects based on statistical tests (e.g., generalised linear models) or ordination methods (e.g., correspondence analysis). Thus, we excluded articles from marine environments, reviews, meta-analyses and modelling, and publications that did not provide information on water quality parameters (e.g., indirect effects of fire on aquatic biota), that evaluated the effect of transfer of ashes and toxic substances unrelated to fire on water quality (e.g., volcanic eruptions), and that showed the impacts of fire in a different context (e.g., paleoecological studies).

From the selected articles, we extracted the following information: (1) year of the publication, (2) country where the study was conducted, (3) type of studied aquatic environment: lotic or lentic, (4) fire origin: wildfire (natural or human-started), prescribed or experimental, (5) water quality parameter(s) recorded, (6) category(ies) of the water quality parameter(s) recorded: physical or chemical (Omer 2019), and (7) response to fire of the water quality parameter(s) recorded: altered (significant increase or decrease) or unaltered (non-significant differences). Most articles conducted statistical analyses for multiple water quality parameters, so each relationship studied between a particular parameter and a specific response within an article was termed as a case, the sample unit in our database.

### Data analysis

To test differences in the frequency of responses to fire between physical and chemical water quality parameters, we analysed a contingency table considering the category of the water quality parameter recorded (2 rows; physical or chemical) × altered/unaltered responses of each water parameter (2 columns). We analysed significant departures from expected frequencies with the Fisher exact test, performed with R software (R Development Core Team 2020). Contingency tables allow the inclusion of the simplest and standard response that can be extracted from the articles (altered –increase, decrease– and unaltered –neutral–; see Teixido et al. 2021). Thus, we included as many studies as possible in our assessment, and the many different ways in which results were reported, by testing for significant differences in the observed frequency of the responses of water quality parameters to fire.

# Results

## Global research patterns

We found 54 articles published between 1976 and 2019 studying the effects of fire on physical and chemical water quality parameters of freshwater ecosystems (Supplementary Information). The number of publications positively increased over time (Fig. 1). This increase was sizable in the last decade; whereas from 1976 to 2009 the number of published articles was relatively low (18 studies; mean ± SE = 1.1 ± 0.6 studies per year), publications were doubled between 2010 and 2019 (36 studies; mean ± SE = 3.2 ± 1.7 studies per year). Research showed a clear bias towards the West and extensive geographic gaps. Studies were only conducted across nine countries and the Latin American region was overlooked (Fig. 2). The United States comprised the highest percentage of publications (51%), followed by Australia (20%), Portugal (9%), Canada (6%), Singapore and the United Kingdom (4% each), and Russia, South Africa and Spain (2% each, corresponding with one article).

The lotic systems, including rivers, streams and hydrographic basins were the environments with the highest number of studies (78%), whereas research in lentic systems was conducted in 20% of the publications. Only one article included both lentic and lotic environments (2% of the total). Most of the publications considered wildfires (72%), while studies addressing the effects of prescribed or controlled fire accounted for 20% of research. Only 8% of the studies represented the effect of experimental fire, conducted either in the field or the laboratory.

## Effects of fire on water quality parameters

Overall, 57 chemical and 17 physical water quality parameters were evaluated. Accordingly, the number of cases reported for chemical parameters (304) was about 4-times higher than for physical parameters (77) (Table 1). Among the 57 chemical parameters analysed, ten comprised about 60% of the 304 cases studied: nitrate (28 cases), total phosphorus (24), total nitrogen (23), ammonium (17), pH (17), calcium (16), magnesium (16), potassium (15), sodium (15) and dissolved organic carbon (13). For the physical parameters, electric conductivity (19 cases), turbidity (15), temperature (11) and total suspended solids (11) comprised about 75% of the cases (Table 1).

On average, fire altered *ca*. 68% of the cases reported for all water quality parameters and this alteration was proportionally similar between chemical and physical properties (66% *vs* 75%; Fisher exact test: $P$ = 0.134; Fig. 3). Among the chemical parameters, the concentration of nutrients (nitrate, total nitrogen, total phosphorus), metal ions (aluminium, iron), alkalinity and dissolved organic carbon were the most frequently increased parameters by fire, whereas dissolved oxygen mostly decreased. On the other hand, nutrient metal ions (calcium, magnesium, potassium, sodium), nutrient salts (ammonium, phosphate, sulphate) and pH showed similar frequencies of altered and unaltered responses to fire (Table 1). Fire-induced alterations of physical parameters were mostly mediated by increases in electrical conductivity, turbidity, total suspended solids, temperature and sediment concentration. Otherwise, depth, Secchi transparency and substrate diameter decreased, although these parameters were only reported by one case (Table 1).

# Discussion

## Global research patterns

The low number of publications analysed in our review shows that the impacts of fire on freshwater ecosystems are less considered when compared to the effects on functioning, soil properties and biodiversity of terrestrial environments (e.g., Butler et al. 2018; Pastro et al. 2014; Vasconcelos et al. 2017; Wan et al. 2001). Moreover, a growing body of studies has reviewed the effects of fire on composition, structure and transformation of terrestrial ecosystems and their biodiversity (e.g., Certini et al. 2021; González-Pérez et al. 2004; He et al. 2019; Kelly et al. 2020; Santín and Doerr 2016). Our study encompasses a global synthesis of the current state of knowledge and impacts of fire on freshwater ecosystems, adding new insights to the underrepresentation of studies about fire and aquatic environments (Brixby et al. 2015). However, the temporal distribution of studies revealed a disproportionate increase in the publications during the last decade. Concern about the risks of the increased frequency and severity of wildfires to water supply is growing across the scientific community (Robinne et al. 2021). The widespread interest over recent years on the impacts of fire is related to climate-associated perturbations, such as high temperatures and prolonged droughts, where substantial increases in the probability of wildfires and area of burned vegetation are expected (Jolly et al. 2015; Robinne et al. 2021). Impacts of fire intensity on freshwater ecosystems based on climate change projections include alterations on the structure and resilience of these environments, recreational use of water bodies, and drinking water treatment (Loiselle et al. 2020). Under the unceasing global warming scenario and resulting water availability, we encourage the scientific community to broaden knowledge of fire impacts on freshwater systems.

We found major gaps in the global distribution of studies, mostly concentrated in North America, Australia and a few European countries. Geographic biases are pervasive issues in ecology and conservation biology that result in oversampled areas, countries and ecosystems (Cook et al. 2013; Nuñez et al. 2021). Some non-exclusive reasons are feasible to account for the predominance of fire-related studies across the reported regions, associated with more research institutions, science investment, native English speak and fire intensity. Overall, ecological research is disproportionately skewed to western or economically developed countries, especially to the United States (Nuñez et al. 2021). In parallel, the dominance of studies for this country may be induced by the general increase of burned area in the last decades due to high fuel loads (i.e., plant material), human-population growth in urban areas, and climate change (Doerr and Santín 2013). In the United States, wildfires between 1984 and 2014 affected approximately 6% of the total length of lotic ecosystems, becoming one of the major drivers of deterioration of freshwater systems (Ball et al. 2021). Moreover, both the United States and Canada are listed among the countries most affected by wildfire events and subsequent economic damage recorded (Doerr and Santín 2013). Similarly, Australia is constantly affected by wildfires, which are expected to increase due to global warming (Yu et al. 2020). Fires in this country largely deteriorate the soil, water and air quality, with severe impacts on biodiversity and water supply (Silva et al. 2020). Across the European countries, Portugal, Russia and Spain are traditionally three of the most affected countries by wildfires (Doerr and Santín 2013; Migiro 2018). Specifically, Portugal and Russia record an annual average of *ca*. 18,000 fires and, in 2016, fires destroyed about 10% of Portugal's forests and 2.5 M ha of protected areas in Russia (Migiro 2018).

Still, some regions of the world extensively prone to wildfires such as Central and South America, Sub-Saharan Africa and Southern Asia (see Fig. 4 in Doerr and Santín 2013; see also historical records at https://firms.modaps.eosdis.nasa.gov/map) were overlooked. The deficiency of studies in these regions is worrying not only in terms of aquatic wildlife conservation, but also for human needs. Neglected research may lead to less assertive institutional responses and decision makings about water conservation and supply, while hydric requirements are incessantly increasing and water availability decreasing, especially in water-deficit countries from Africa and Asia (Baggio et al. 2021; Leal Filho et al. 2022). However, the interplay between hydrographic characteristics and scientific logistics of some countries may be suitable to encourage researchers to conduct fire-related studies and, ultimately, understand the impacts of fire on freshwater ecosystems in the neglected regions. For example, Brazil, China and India are among the ten countries with the most freshwater bodies and resources (Gleick et al. 2006; Misachi 2018) and with an advanced and growing ecological research in terms of articles published (Nuñez et al. 2021). We call future studies to consider the impacts of fire on freshwater ecosystems across neglected regions of Latin America, Africa and Asia, and encourage the scientific community of leading countries such as Brazil, China and India to promote this research.

We also recorded ecological biases based on the freshwater environments evaluated, as lotic systems (e.g., rivers) were mostly considered in relation to lentic systems (e.g., lakes). Although lentic systems cover a much greater volume of freshwater on Earth than lotic systems (*ca*. 43:1; Shiklomanov 1993; USGS 2013), research on ecology and biodiversity is commonly biased to rivers and streams when compared to lakes and other lentic environments (e.g., Veach et al. 2021; Wurtsbaugh et al. 2015). Although the responses to the effect of fire on water quality may be similar in both environments (e.g., nutrients and temperature; Naylor et al. 2012; Sundarambal et al. 2010), fire effects on lentic watersheds have not still been properly addressed and require further consideration (McCullough et al. 2019). We therefore propose additional sampling efforts on lakes and other lentic systems to improve our knowledge of how fire may impact the physicochemical characteristics of these ecosystems in a changing world.

## Effects of fire on water quality parameters

Water is an essential resource and its quality classified according to physical, chemical and biological characteristics, establishing environmental change-sensitive parameters (Omer 2019). However, the quality of water attributed to freshwater ecosystems is very dynamic and variable over time, space and use of this resource (Wyk and Scarpa 1999). For example, although the same set of parameters can be utilised to characterise water quality across different environments (e.g., ponds, rivers, lakes), similar parameter values would be unexpected. In brief, water quality is intrinsically associated with its use, region and environment of origin, with variable parameters associated with human activities and the functionality and conservation of aquatic ecosystems (Brooks et al. 2015; Keeler et al. 2012; Wyk and Scarpa 1999). In this review, we compiled an extensive set of water quality parameters, mostly chemical, used to capture their sensitivity to fire, linking a typically terrestrial disturbance to freshwater ecosystems. From this set, a few parameters were mostly used as chemical water properties in the studies, especially nitrogen and phosphorus. Publications considering these nutrients essential in freshwater systems cover a broad range of scopes beyond fire impact, from drinking water quality (e.g., Nieder et al. 2018) to trophic status (e.g., Sager 2009). Across the physical variables, electrical conductivity and temperature were recurrent, as these are relevant parameters for ecosystem functioning and widely used in environmental monitoring of aquatic habitats (Hayashi 2004).

Interestingly, physical and chemical water quality parameters were equally vulnerable to the effects of fire. Our results also revealed a predominance of increased responses of these parameters following wildfires (e.g., metal ions, nutrient concentration, temperature, turbidity). In limnological terms, increases in chemical parameters such as nutrient concentrations, metal ions, dissolved organic carbon, and subsequent increases in alkalinity derived from sediment fluxes, runoff and ash deposition after fires, are also associated with decreases in dissolved oxygen, as well as higher values of several physical parameters as electrical conductivity, sediment concentration, temperature, total solids and turbidity (Brito et al. 2021; Hohner et al. 2016; Smith et al. 2011). Wildfires are a major driver of nitrogen cycling and its export from terrestrial to aquatic systems, consequently degrading water quality (Gustine et al. 2021). High fire-mediated concentrations of nitrogenous compounds in freshwater ecosystems can remain elevated for decades. Thus, the transfer of nutrients (e.g., nitrate) into these environments may ultimately exceed the demand of the biota, increasing their susceptibility to eutrophication and harmful algal blooms until the recovery of terrestrial vegetation, when plant demand for nutrients reduces nitrogen availability (Rhea et al. 2021). Subsequently, eutrophication of freshwater ecosystems and proliferation of primary producers may largely affect water quality by decreasing dissolved oxygen and light absorbance, or increasing temperature and turbidity (Carignan and Lamontagne 2000; Monaghan et al. 2019; Oliver et al. 2012). Therefore, the set of physicochemical properties of freshwater ecosystems are interconnected and mutually dependent water quality parameters mostly sensitive to and indirectly affected by fire. Evaluating the interplay between these chemical and physical characteristics following wildfires is crucial to fully understand the functioning, resilience and vulnerability of continental aquatic environments worldwide.

## Implications for biodiversity and human needs

Alterations in water physicochemical conditions following fire can lead to freshwater pollution and subsequent changes in aquatic biota and ecosystem services. For example, fire causes short-term declines in microalgae and periphyton communities due to accumulations of contaminants and polycyclic aromatic hydrocarbons (Silva et al. 2015). However, benthic algae populations have a long-term potential to recolonize and increase following fire disturbance (Rugenski and Minshall 2014). The effects of fire-mediated environmental disturbance reduce both the biomass and the composition of decomposer organisms, such as bacteria and aquatic fungi, and therefore indirectly affect the trophic networks of aquatic ecosystems (Carvalho et al. 2019). Similarly, chemical composition and toxicity of fire-produced ashes induce acute immobility of zooplankton (Harper et al. 2019). In addition, fire impacts commonly affect macroinvertebrate diversity, replacing rare species by tolerant, more generalist, species (Monaghan et al. 2019; Xu et al. 2014). Post-fire runoff also causes anomalies in the feeding behaviour of shredder macroinvertebrates, consequently affecting ecological processes, since aquatic shredders play an important role in detritus-based food webs of lotic ecosystems (Pradhan et al. 2020). Likewise, the experimental exposure to an aqueous extract of ash solutions increases the mortality rates of a mollusc species (Silva et al. 2016). For fishes, fire-induced water toxicity negatively affects resource-specialist stream species (e.g., *Salmo trutta*), whereas generalist cyprinids remain unaltered (Monaghan et al. 2016). In fact, fishes can interestingly be fire-resilient, decreasing abundance and recolonizing the river after years from the disturbance (Caldwell et al. 2013; Dudham et al. 2007). Other indirect effects of fire on fish assemblages include increased water temperatures and turbidity, resulting in declines of trout populations (Hitt 2003; Rust et al. 2019).

Otherwise, less is known about the effects of fire on herpetofauna, birds and mammals that use or temporarily inhabit freshwater ecosystems, regardless of being permanent-resident species. The impacts of fire on amphibians are spatially and temporally variable, and mostly focused on terrestrial species or terrestrial life stages of aquatic breeding species (Hossack and Pilliod 2011; Pilliod et al. 2003). Still, evidence shows that stream amphibian species are more negatively affected by fire than terrestrial amphibians (Bury 2004). More recent studies have also demonstrated that breeding occurrence and species richness significantly decline across rivers and streams after fire (Larson 2014; Muñoz et al. 2019). For reptiles, Lovich et al. (2017) recorded high mortality rates in the southwestern pond turtle related to low levels of dissolved oxygen and high salinity in a lake in California following a large wildfire. Piscivorous and water-feeding birds and mammals may also indirectly suffer the impacts that fire causes on water physicochemical conditions of rivers and lakes. For example, high fire-related mercury concentrations have been found in both herring gull eggs (Hebert et al. 2021) and semi-aquatic mustelid fur and stomach content (Eccles et al. 2020). However, prescribed fire enhanced foraging success and prey captures of long-legged wading birds in a grass-dominated wetland by creating burned areas with short-term shallow water habitats (Venne and Frederick 2013). We suggest that further water-fire research on semi-aquatic and non-fish aquatic vertebrates would be recommended to ultimately improve our understanding of how fire indirectly impacts top trophic levels, food webs and ecological complexity of freshwater ecosystems.

An extensive array of ecosystem services may be affected by fire, among which water quantity, soil retention, pest management and natural hazard regulation have been largely considered (Vukomanovic and Steelman 2019). For freshwater ecosystem services, major concerns of the impacts of fire are focused on water availability and demands for human requirements (e.g., Hallema et al. 2018; Robinne et al. 2018; Robinne et al. 2021). Constant declines in water quantity and quality have become a growing global challenge to human health and sustainable development, especially under the projected drought scenarios associated with climate change and the exponential population growth (Baggio et al. 2021; Emelko et al. 2011; Hallema et al. 2018). Following fire, the increased concentrations of contaminants and toxic constituents (e.g., arsenic, cyanides, heavy metals) and alterations in the composition of organic matter deposited in watersheds, which can form disinfection by-products related to cancer and reproductive development during water treatment process, impact drinking water supplies (e.g., Hohner et al. 2016; Pennino et al. 2022; Smith et al. 2011). Although wildfires can endanger potable water resources, little is still known about the global assessment of the impacts on water supplies. This is particularly important to achieve the Agenda 2030's Goal 6, that seeks to protect and restore freshwater ecosystems, increase water quality, reduce the number of people suffering from water scarcity, and achieve universal and equitable access to drinking water (UN General Assembly 2015).

# Conclusions

Our study demonstrates that fire frequently affects water quality parameters of freshwater ecosystems. A broad set of chemical and physical parameters were analysed, which were altered by fire in similar proportions. However, fire-mediated effects on freshwater ecosystems are still poorly considered in relation to terrestrial environments and research strongly biased towards a few western countries. Freshwater ecosystems harbour a large biodiversity worldwide, but are habitats highly vulnerable to anthropogenic actions that are increasingly undergoing the impacts of global environmental change. Our review brings key findings to steer future sampling efforts and subsequently promote a more in-depth understanding of the impacts of fire on freshwater ecosystems. Overall, considering the biased research and the flawed knowledge on the effects of fire on water quality of freshwater ecosystems and subsequent impacts on biodiversity and human needs, the persistent vulnerability of these environments under the climate change scenarios, and the exponential human population growth, is essential to ensure sustainable development, fostering progress while protecting the freshwater systems. Our results may ultimately guide applicable conservation policies for wildlife, water management strategies and sustainability of these environments.

# Declarations

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## Declarations

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### Competing interests

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome. Our research is based on data from literature, so we confirm that did not conduct any work with wild or captive animals. Therefore, no ethical policy relative to conservation considerations is applicable (e.g. BOU ethical policy).

### Data availability statement

The raw data that support the findings of this study will be available in a repository once the article is accepted. The references used in this review are available within the supplementary information file.

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# Tables

**Table 1**. Set of all the analysed chemical and physical water quality parameters and number of cases reported for altered (i.e., increase or decrease) or unaltered (i.e., neutral) responses to fire of these parameters across the 54 publications included in this review. Numbers in brackets indicate the percentage of cases over the total number of cases reported for each parameter.

| Water quality parameters | Type of water quality parameters | Response | | |
|---|---|---|---|---|
| | | Altered | | Unaltered |
| | | Increase | Decrease | |
| Acid neutralising capacity (mEq/L) | Chemical | - | 1(100) | - |
| AI - Autotrophic Index (g/m$^2$) | Chemical | 1(100) | - | - |
| Alkalinity (mg $CaCO_3$/L) | Chemical | 5(71.4) | 1(14.3) | 1(14.3) |
| Aluminium (Al3+) (mg/L) | Chemical | 4(80.0) | 1(20.0) | - |
| Ammonium ($NH_4$+) (mg/L) | Chemical | 7(41.2) | 4(23.5) | 6(35.3) |
| Antimony (Sb3+) (mg/L) | Chemical | 1(100) | - | - |
| Arsenic ($AsH_3O_4$) (mg/L) | Chemical | 1(50.0) | - | 1(50.0) |
| Benthic organic matter (g/m$^2$) | Chemical | 2(100) | - | - |
| Bicarbonate ($HCO_3$) (mg/L) | Chemical | 1(33.3) | 1(33.3) | 1(33.3) |
| Bromine ($Br^-$) (mg/L) | Chemical | - | 1(50) | 1(50) |
| Calcium (Ca2+) (mg/L) | Chemical | 7(43.8) | 2(12.4) | 7(43.8) |
| Chlorine ($Cl^-$) (mg/L) | Chemical | 3(33.3) | 2(22.2) | 4(44.5) |
| Chromium (Cr3+) (mg/L) | Chemical | 1(100) | - | - |
| Copper (Cu2+) (mg/L) | Chemical | 1(50.0) | - | 1(50.0) |
| Dissolved black carbon (mg C/L) | Chemical | 1(100) | - | - |
| Dissolved inorganic carbon (ppm) | Chemical | 1(100) | - | - |
| Dissolved organic carbon (ppm) | Chemical | 7(53.8) | 2(15.4) | 4(30.8) |
| Dissolved organic phosphorus (mg/L) | Chemical | - | - | 1(100) |
| Dissolved oxygen (mg/L) | Chemical | 1(10.0) | 7(70.0) | 2(20.0) |
| Dissolved silica ($SiO_2$) (mg/L) | Chemical | - | 1(33.3) | 2(66.7) |
| Filterable reactive phosphate (mg/L) | Chemical | 2(100) | - | - |
| Fine particulate organic matter (mg/L) | Chemical | 1(100) | - | - |

| | | | | |
|---|---|---|---|---|
| Fluorine ($F^-$) (mg/L) | Chemical | - | - | 2(100) |
| Hardness (mg $CaCO_3$/L) | Chemical | 1(25.0) | 1(25.0) | 2(50.0) |
| Heavy metals (mg/L) | Chemical | - | - | 1(100) |
| Iron (Fe2+) (mg/L) | Chemical | 4(57.1) | 1(14.3) | 2(28.6) |
| Lead (Pb2+) (mg/L) | Chemical | 1(100) | - | - |
| Lithium (Li+) (mg/L) | Chemical | 1(100) | - | - |
| Magnesium (Mg2+) (mg/L) | Chemical | 9(56.2) | - | 7(43.8) |
| Major ions (mg/L) | Chemical | 1(100) | - | - |
| Manganese (Mn2+) (mg/L) | Chemical | 2(66.7) | - | 1(33.3) |
| Mercury (Hg2+) (mg/L) | Chemical | - | - | 1(100) |
| Nickel (Ni2+) (mg/L) | Chemical | - | - | 1(100) |
| Nitrate ($NO_3^-$) (mg/L) | Chemical | 16(57.1) | 3(10.7) | 9(32.2) |
| Orthophosphate (mg/L) | Chemical | 2(66.7) | - | 1(33.3) |
| Oxidized nitrogen (NO) (mg/L) | Chemical | - | - | 1(100) |
| Particulate black carbon (mg C/L) | Chemical | 1(100) | - | - |
| pH (H+) | Chemical | 6(35.3) | 3(17.6) | 8(47.1) |
| Phenols ($C_6H_5OH$) (mg/L) | Chemical | 1(100) | - | - |
| Phosphate ($PO_4 3^-$) (mg/L) | Chemical | 2(25.0) | 1(12.5) | 5(62.5) |
| Polycyclic aromatic hydrocarbons (ng/L) | Chemical | 3(100) | - | - |
| Potassium (K+) (mg/L) | Chemical | 8(53.3) | - | 7(46.7) |
| Selenium (Se) (mg/L) | Chemical | 1(100) | - | - |
| Silver (Ag+) (mg/L) | Chemical | - | - | 1(100) |
| Sodium (Na+) (mg/L) | Chemical | 4(26.7) | 3(20.0) | 8(53.3) |
| Soluble reactive phosphorus (mg/L) | Chemical | 3(100) | - | - |
| Sulphur ($S2^-$) (mg/L) | Chemical | 2(100) | - | - |
| Sulphate ($SO_4 2^-$) (mg/L) | Chemical | 3(30.0) | 2(20.0) | 5(50.0) |
| Suspended organic carbon (mg/L) | Chemical | 1(100) | - | - |

| | | | | |
|---|---|---|---|---|
| Thick particulate organic matter (mg/L) | Chemical | 1(100) | - | - |
| Titanium ($Ti^{4+}$) (mg/L) | Chemical | 1(100) | - | - |
| Total inorganic solutes (mg/L) | Chemical | 1(100) | - | - |
| Total Kjeldahl nitrogen (mg/L) | Chemical | 2(66.7) | - | 1(33.3) |
| Total nitrogen (mg/L) | Chemical | 16(69.6) | 4(17.4) | 3(13.0) |
| Total phosphorus (mg/L) | Chemical | 16(66.7) | 2(8.3) | 6(25.0) |
| Vanadium ($V^{2+}$) (mg/L) | Chemical | 1(100) | - | - |
| Zinc ($Zn^{2+}$) (mg/L) | Chemical | 1(100) | - | - |
| Depth (m) | Physical | - | 1(100) | - |
| Electric conductivity (μs/cm) | Physical | 14(73.7) | - | 5(26.3) |
| Light attenuation coefficient (εPAR) | Physical | 1(100) | - | - |
| Refractory black carbon nanoparticles (μg/L) | Physical | - | - | 1(100) |
| Secchi transparency (cm) | Physical | - | 1(100) | - |
| Sediment concentration (mg/L) | Physical | 4(100) | - | - |
| Sedimentation rate (kg/s) | Physical | 1(100) | - | - |
| Specific conductance (μS/cm) | Physical | - | - | 1(100) |
| Streamflow ($m^3/s$) | Physical | 2(100) | - | - |
| Substrate diameter (cm) | Physical | - | 1(100) | - |
| Temperature (°C) | Physical | 8(72.7) | - | 3(27.3) |
| Thick inorganic sediment (mg/L) | Physical | - | - | 1(100) |
| Total dissolved solids (mg/L) | Physical | 3(75.0) | - | 1(25.0) |
| Total suspended solids (mg/L) | Physical | 9(81.8) | - | 2(18.2) |
| Turbidity (NTU) | Physical | 12(80.0) | - | 3(20.0) |
| Ultraviolet absorbance (SUVA254) (L/mg-m) | Physical | - | - | 1(100) |
| Volatile suspended sediments (mg/L) | Physical | 1(50.0) | - | 1(50.0) |
| **Total** | - | 213(55.9%) | 46(12.1%) | 122(32.0%) |

# Figures

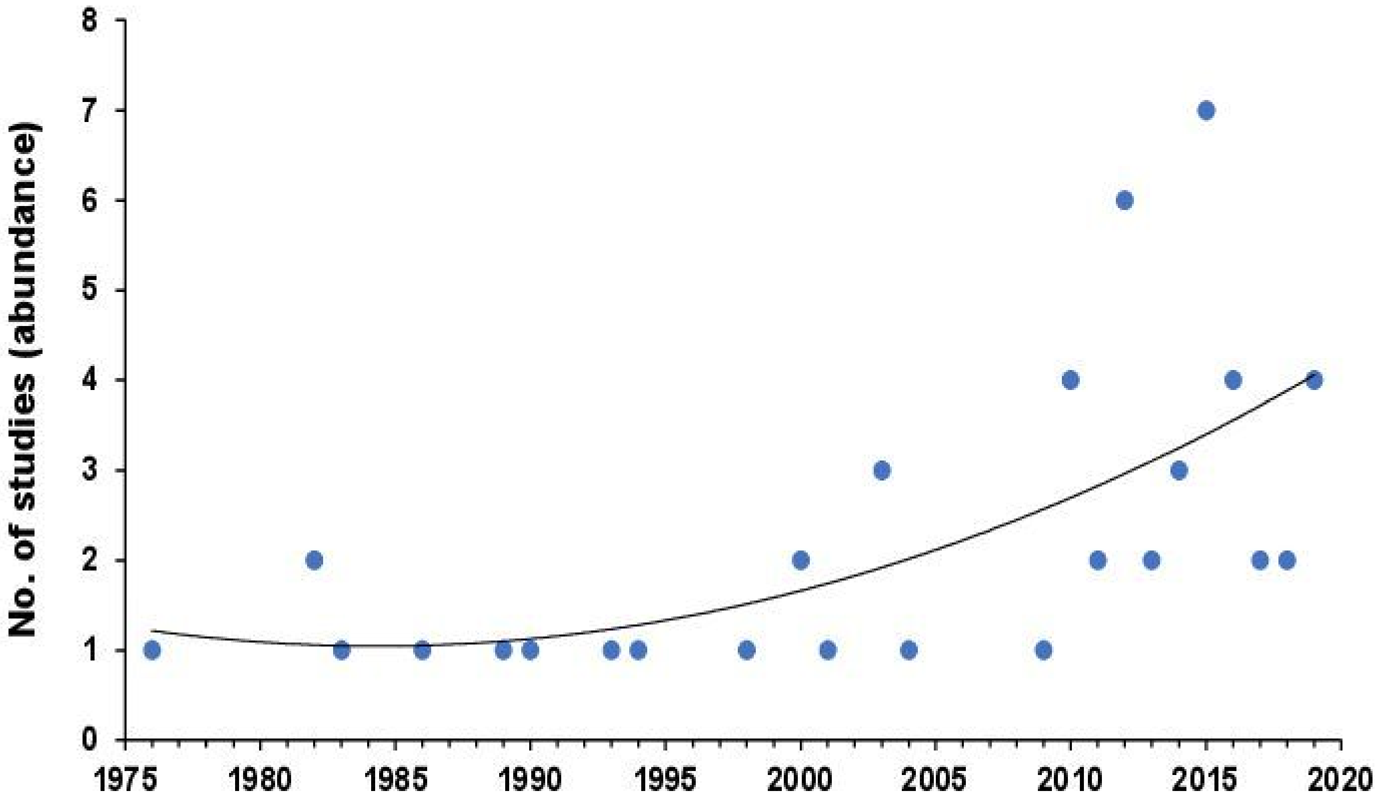
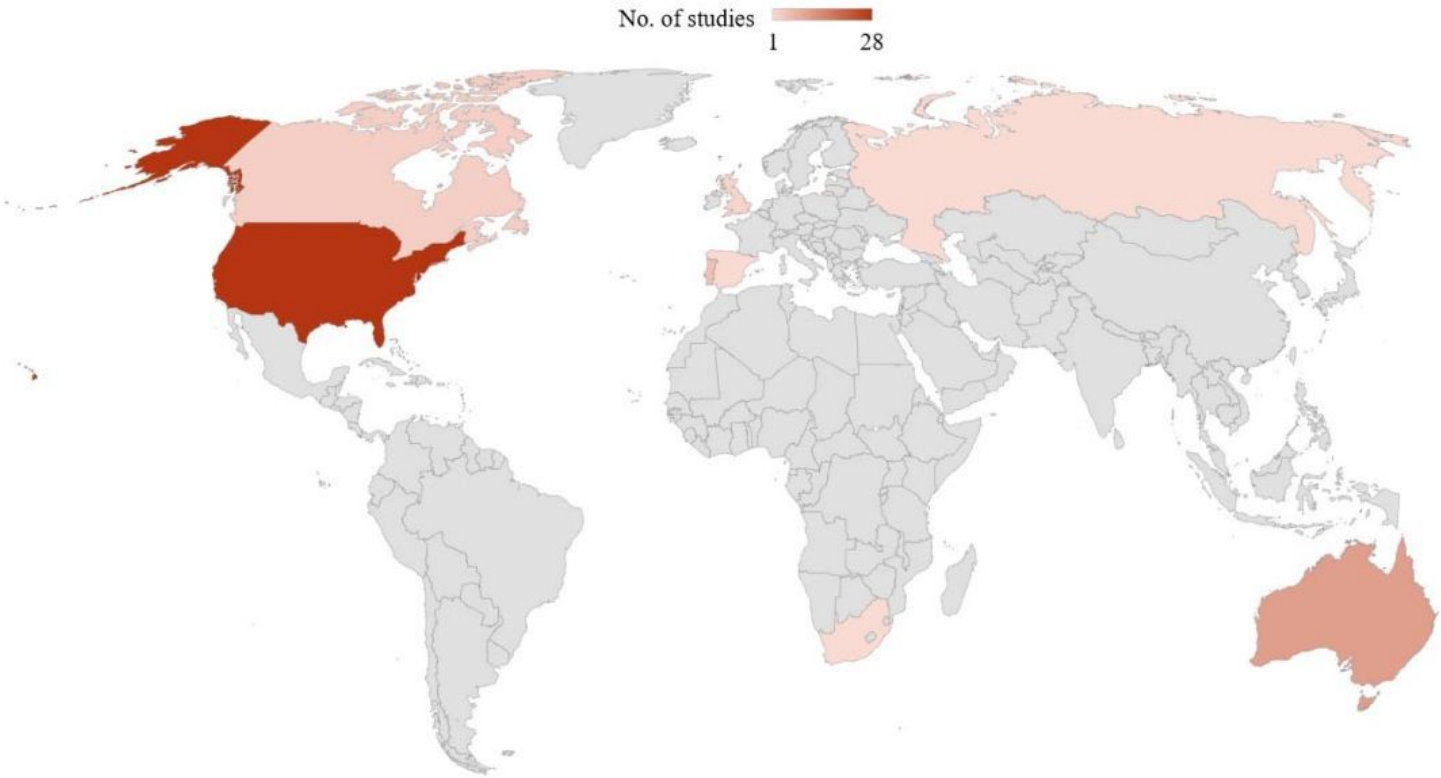



**Figure 1**

Temporal distribution of the publications evaluating the effects of fire on water quality parameters of freshwater ecosystems. The curve shows the best-fit adjustment with a 2nd-order polynomial correlation ($R^2$ = 0.39, *P* = 0.005).




## Figure 2

Abundance and global geographic distribution of the publications evaluating the effects of fire on water quality parameters of freshwater ecosystems between 1976 and 2019.

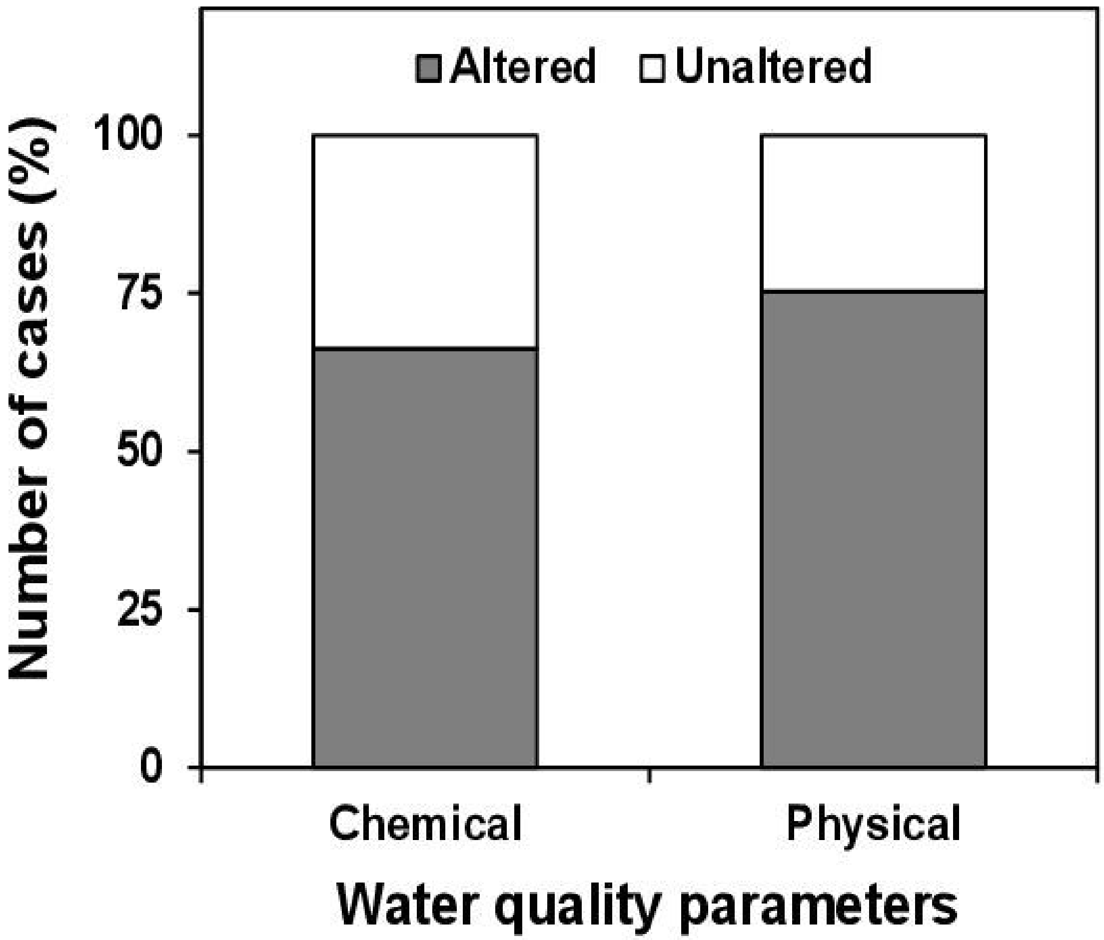



**Figure 3**

Relative observed frequencies of altered and unaltered responses to fire of chemical and physical water quality parameters. The frequency of the responses was similar between both parameters (Fisher exact test, $P = 0.134$).

## Supplementary Files

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