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LETTER

Forest fire effects on stream water quality at continental scales: a meta-analysis

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Abstract

Forested watersheds supply over two thirds of the world’s drinking water. The last decade has seen an increase in the frequency and intensity of wildfires that is threatening these source watersheds, and necessitating more expensive water treatment to address degrading water quality. Given increasing wildfire frequency in a changing climate, it is important to understand the magnitude of water quality impacts following fire. Here, we conducted a meta-analysis to explore post-fire changes in the concentrations of nitrogen (N) and phosphorus (P) species, dissolved organic carbon, and total suspended sediments in 121 sites around the world. Changes were documented over each study’s respective duration, which for 90% of sites was five years or fewer. We find concurrent increases in C, N and P species, highlighting a tight coupling between biogeochemical cycles in post-fire landscapes. We find that fire alters N and P speciation, with median increases of 40%–60% in the proportion of soluble inorganic N and P relative to total N and P. We also found that fire decreases C:N and C:P ratios, with median decreases ranging from 60% to 70%. Finally we observe a ‘hockey stick’-like response in changes to the concentration distribution, where increases in the highest concentration ranges are much greater than increases at lower concentrations. Our study documents strong heterogeneity in responses of water quality to wildfire that have been unreported so far in the literature.

1. Introduction

Forested watersheds sustain a significant portion of the world’s water supply needs (Dudley and Stolton 2003, Rockström et al 2014). The ecological functioning of many forest biomes is sustained by fire (McLauchlan et al 2020), but fire can also degrade water quality in streams draining forested watersheds, and threaten water-provisioning ecosystem services (Emelko et al 2011, Kinoshita et al 2016). These services are under further threat as wildfire regimes across the planet continue to shift in frequency, extent, and severity (Westerling 2006, Moritz et al 2012, Li et al 2018), partly in response to anthropogenic warming and climate change (Abatzoglou and Williams 2016, Seidl et al 2017, Creed and van Noordwijk 2018, Khorshidi et al 2020, Jain et al 2022). This dual threat of climate change and unpredictable fire regimes demands greater understanding of the altered landscape processes after fire that can degrade downstream water quality, and impact the ability of water providers to produce safe drinking water (Emelko et al 2011, Hohner et al 2019, Robinne et al 2021).

Decades of wildfire studies have highlighted the effects of wildfires on water resources, including modifications of the hydrologic cycle (Hallem et al 2017, 2018, Basso et al 2020, Maina and Siirila-Woodburn 2020), the geomorphic regime (Ice et al 2004, Shakesby and Doerr 2006), and element cycling and export (Hauer and Spencer 1998, Bladon et al 2008, Emelko et al 2016, Rust et al 2018, McCullough et al 2019, Basso et al 2020, Crandall et al 2021, Mishra et al 2021). While most studies of water quality in post-wildfire landscapes have focused on one or two key variables (e.g. sediments, nitrogen, phosphorus, and carbon), the few that have analyzed the coupling of multiple element
cycles have allowed us to gain critical insights. For example, Noske et al (2010) document how the fluxes of total phosphorus and suspended sediment were strongly linked post-fire in Australian streams. Similarly, in a Canadian Rocky Mountain stream, Emelko et al (2016) observed how phosphorus specification shifted after fire towards more bioavailable forms, while nitrogen to phosphorus ratios decreased, likely freeing stream biota from phosphorus limitation and facilitating algal blooms (Bladon et al 2008, Silins et al 2014). In an Arctic stream in Siberia, Rodriguez-Cardona et al (2020) observed that decreasing dissolved organic carbon (DOC) concentrations post-fire reduced nitrate uptake efficiency by stream biota, thus increasing downstream nitrate export. Another study by Morales et al (2013) measured soil and stream export of nitrogen, and showed preferential loss of nitrogen relative to carbon from the studied volcanic soils after fire. Coupled biogeochemical cycles in post-fire landscapes are likely key factors that control downstream ecosystem responses, such as eutrophication and algal blooms, thus requiring further exploration.

While most studies focus on mean concentration changes after fire, drinking water treatability is often by extremes in precipitation, flow, and water quality. Wilkinson et al (2006) documented that fire elevates the concentration of suspended sediment and phosphorus during rare high flow events. Indeed, short-term disturbances such as the annual spring flooding in many rivers along with larger post-fire floods and mudslides increase suspended sediment and pose a large and immediate challenge to drinking water treatability (e.g. post-fire flood events; Writer et al 2014, Murphy et al 2015, 2018). Even if the impact on water quality is short lived, extreme events may change the distribution of nutrients across a catchment, for example by creating a reservoir of finesediment-associated phosphorus in gravel bedded rivers (Emelko et al 2016). More needs to be known of the behavior of water quality during extreme events after fire.

Finally, most studies of fire impacts on water quality have been site specific. Multi-site and multi-study analyses include a review paper by Bitner et al (2001), a review paper by Smith et al (2011), and a large data synthesis by Rust et al (2018). Bitner et al (2001) reviewed how multiple element cycles are altered by fire, including in soils, sediment-associated elements, and exported in streams. Smith et al (2011) reviewed how fire altered stream water concentrations of suspended sediment, phosphorus, nitrogen, and turbidity across many studies. More recently, a study by Rust et al (2018) analyzed a post-fire water quality dataset of 73 analytes in 153 burned watersheds in the western US. In a followup study, Rust et al (2019) analyzed drivers of the post-fire water quality response, and found that the increase in nitrogen and phosphorus loads was related to the increase in the extent of the area burned at a moderate to high severity.

Here, we build on this body of research and use a meta-analysis approach to explore the interactions between element cycles in post-fire landscapes, and the effect of fire on the concentration distribution. Our specific objectives are to: (a) quantify the effect of fire on the changes in concentrations of suspended sediments, nitrogen, phosphorus and carbon species, (b) quantify the degree of covariation between the concentrations of these elements in post-fire landscapes, and (c) quantify the effect of fire on concentration distributions.

2. Methods

2.1. Meta-analyses

All data and code used in this study are provided in an online repository (Hampton 2022). We used keyword searches in the Scopus database (Elsevier B.V.), using the following search terms: (‘wildfire’ OR ‘fire’ OR ‘burn’) AND (‘water’ OR ‘stream’ OR ‘river’ OR ‘runoff’ OR ‘discharge’ OR ‘export’) AND (‘chemistry’ OR ‘treatment’ OR ‘supply’ OR ‘nutrient’ OR ‘nitrogen’ OR ‘carbon’ OR ‘phosphorus’ OR ‘quantity’ OR ‘water quality’) to isolate publications specific to detecting water quality trends in relation to forest fire. The search was applied to the Title, Abstract, and Keywords of the papers. The search was conducted in August 2019, and returned 155 publications (table SI-1 available online at stacks.iop.org/ERL/17/064003/mmedia) that were further screened using the following criteria: (a) the study focused on water quality in streams following wildfires (not on soil–water solute concentrations, nor on lakes), (b) the study measured at least one of the following water quality parameters: nitrogen or phosphorus in organic (e.g. dissolved organic nitrogen (DON)), total (e.g. total nitrogen (TN), total phosphorus (TP)), or inorganic forms (e.g. nitrate (NO$_3^-$), ammonium (NH$_4^+$), phosphate (PO$_4^{3−}$)); organic carbon (DOC), or total suspended sediment (TSS), (c) studies that specifically referenced the use of fire suppressants or chemical fertilizers on the landscape were excluded, to remove their possible chemical influence.

The meta-analysis presented in this paper draws data from 34 publications, and includes data from both wildfires and prescribed burns. Locations of the studies are shown on a world map in figure 1, with a total of 121 unique watersheds. The United States has the most studies (20), followed by Australia (6) and Canada (5). Other study locations included Portugal, Spain, and South Africa. It is notable that since August 2019, numerous papers on these topics have been published, representing increased geographic diversity. Future examination of this literature will be able to minimize the bias of studies towards the United States, Australia, and Canada.
2.2. Data extraction and harmonization

Data were either extracted from tables or figures in papers. We used WebPlotDigitizer version 4.2 (Rohatgi 2019) to extract data from figures. We also recorded study metadata for the dates of fires, so that concentrations can be compared temporally to the fire occurrence. Where graphical data were not included, data were extracted from tables in studies that reported either average pre- and post-fire concentrations of water quality constituents, or annual or monthly values. The majority (19) of studies used data from reference, unburned catchments to compare to data from burned catchments, and these are hereafter referred to as control-impact studies. A smaller group of studies (11) relied exclusively on comparison of pre- and post-fire data, and these are hereafter referred to as before-after studies. In a much smaller subset of studies (4) there was both before-after data, though this was sometimes limited to only certain water quality constituents. When both were present for one variable, we opted to compare fire effects using the control-impact axis. We normalized all concentration units to mg l$^{-1}$ (e.g. mg P l$^{-1}$, mg N l$^{-1}$ and mg C l$^{-1}$). We assumed ‘filterable reactive phosphorus’, ‘soluble reactive phosphorus’, and ‘phosphate’ to functionally measure the same thing (PO$_4^{3−}$). Likewise, we assumed that ‘oxidized nitrogen’ was the same as NO$_3^−$.

2.3. Metrics and statistical analysis

We used several different metrics and normalization strategies to evaluate the effect of fire on the water quality variables across the 81 burned sites. The change metrics used in this study are the CR of mean concentrations (CR$_M$; (Hedges et al 1999, Rosenberg et al 2013), CR of the coefficient of variation (CV) of the concentration distribution (CR$_{CV}$), absolute change (AC), and the decile normalized change (dNC). We used CR instead of more sophisticated metrics like the ‘Hedge’s d’ since the latter requires estimates of the variance of water quality concentrations pre- and post-fire, and a large proportion of our sites did not have enough data to reliably estimate a variance (Borenstein et al 2009).

We define CR$_M$ as the ratio of the mean concentration in the burned to the control catchment for the control-impact studies, or the ratio of the mean concentrations in the post-fire to the pre-fire periods for the before-after studies. This metric was calculated using averaging across all years (CR$_M$), the first five years (e.g. CR$_M$Yr1-5), and for the first year in the dataset (e.g. CR$_M$Yr1). A CR value of 1 indicates no change, while a value of 10 signifies tenfold higher concentrations after the fire relative to the average reference concentration. We define CR$_{CV}$ as the ratio of the CV of the concentration in the postfire period to the CV in the prefire period. Here, CV is defined as the ratio of the mean concentration to the standard deviation in the concentration deviation. The CR$_{CV}$ metric was estimated only for sites with more than three samples in each of the reference and burn periods.

We assessed correlation between co-measured CRs of different parameters. This analysis relied on sites that measured multiple parameters, and on having sufficient data (at least 4 points) to assess the relationship between parameters across sites. We used the non-parametric Kendall’s rank correlation (KRC) to identify significant relationships. KRC allows us to assess the statistical significance of monotonic relationships, and accounts for relationships that may not be strictly linear in shape. KRC also rules out relationships that are heavily biased by large-value outliers, which may cause the linear relationship to be statistically significant, where KRC is not.
The CR metric does not capture either the effect of fire on concentration extremes, or the decrease in concentrations in the years post-fire. Ideally, evaluation of the effect of fire should take into account both these factors; however data is often not available at a fine enough temporal resolution for such analysis. Given that 90% of our sites had data for <5 years, we analyzed the effect of fire on concentration extremes, but did not explore the recovery effect in this study.

To evaluate the effect of fire on concentration extremes, we developed a methodology using concentration decile curves. For this, we isolated a subset of studies where data was available at a higher temporal resolution (at least ten samples in the pre- and post-fire periods). The methodology is illustrated in figure 2 using data from one burned and reference catchment pair (Bladon et al 2008, figure 2(a)). We grouped the two time series into deciles, and estimated the decile specific mean concentration for the reference and burned catchments (figure 2(b)). We then estimated the decile-specific absolute change (dAC; figure 2(c)) by subtracting the decile-specific mean concentration of the Burned (red line in figure 2(b)) catchment from the corresponding mean concentration of the reference catchments (blue line in figure 2(b)). Finally, we divided the dAC for a site by the AC for that site across all concentrations to estimate the dNC (figure 2(d)). The AC is estimated by subtracting the mean concentrations of the reference period from the mean concentration of the burned period. The dNC (figure 2(d)) showed a distinct ‘hockey stick’ pattern, where at higher deciles (9 or 10) there was the largest increase in concentration. A benefit of our decile-based analysis is that we can accommodate sites with unequal numbers of burned and reference samples. This altered ratio allows us to compare across sites, where total changes range widely in magnitude along with the reference concentrations.

2.4. Attribution analysis

We conducted an analysis of catchment predictor variables and the water quality response variable CR\_M. Predictor variables included burn type (natural or prescribed), fire intensity (low, medium, high), percent catchment burned, catchment area, average concentration during the control period, and catchment slope. Studies were unreliable in providing climatic context of their catchments, so we estimated the aridity index for each catchment from a global raster dataset (Trabucco and Zomer 2018). Relationships were only analyzed if at least 20 catchments had corresponding variables. Correlation between continuous variables was tested using KRC, while response variables were compared with categorical predictor variables using the Kruskal–Wallis test (KWt). Both
methods were used from the using the ‘stats’ package in R Core Team (2022). Following the methods of Rust et al (2019), conditional inference trees were used to determine whether any response variables had threshold responses to the predictor variables. We used the ctree function from ‘partykit’ (Hothorn et al 2006).

3. Results and discussion

3.1. Study metadata

Our meta-analysis identified 34 studies distributed around the world (figure 1 and table SI-1) that represented data from 121 unique study catchments (of which 81 were burned). Catchment slopes ranged from 0% to 70% (median 20%), catchment area ranged from 0.04 to 10^5 hectares (median 3500 ha), and annual precipitation ranged from 18 mm to 3300 mm (median 820 mm) across our study sites (table SI-2). The most commonly sampled parameter was NO₃⁻ (at 67 of 81 sites; figure 3(a) and table SI-3), followed by TP (41), TN (31), NH₄⁺ (30), TSS (26), PO₄³⁻ (20), DOC (17), and DON (14). While not used further in this meta-analysis, the diversity of other parameters was notable: 14 studies sampled for major cations (incl. K, Ca, Na, Mg), 10 for pH, 5 for dissolved O₂, 4 for other dissolved metals (incl. Fe, Mn), and 3 for DON. Only 47% of sites had more than one year of data post-fire, with the greatest data density for NO₃⁻ (figure 3(a)). Further, only 9% of sites sampled beyond five years after the fire. This highlights the propensity of wildfire studies to focus on collecting samples over a short timeframe, making it challenging to evaluate recovery times.

Studies also had a very wide range in the number of samples collected, with sampling frequency ranging from 1 to over 50 samples per year. Figure 3(b) highlights the wide range of sample numbers, with NO₃⁻ having by far the most studies and about a quarter of studies having greater than ten samples per year. For most parameters, about half of sites had a sample density of ten samples or greater per year, with notable data deficiency for NH₄⁺, DON, TN, and TP (figure 3(b)).

3.2. Concentration changes between pre-fire and post-fire periods

Most sites documented an increase in concentrations across the constituents analyzed, with a median CRₘ of 2.1 for NO₃⁻, 1.8 for TP, and 1.3–1.5 for NH₄⁺, PO₄³⁻, TN, DOC, and TSS (figure 4(a)). The range of increases across sites was highly variable, with the highest ranges for CRs observed for NO₃⁻, PO₄³⁻, and TSS, while NH₄⁺, TN, and DON had smaller ranges (figure 4(a)). We found CRₘ < 1 for about 38% of sites for TSS and 18% of sites for NO₃⁻, indicating that for those sites post-fire concentrations were lower than pre-fire concentrations. Our documented CRₘ values are similar to those found by Rust et al (2018) who synthesized data from a large number of wildfire-impacted catchments in the western US (table SI-4). We tested whether study duration influenced CRₘ by comparing the all-time CRₘ (figure 4) with CRₘ based on the first five post-fire years of data (CRₘYr1-5). For all parameters, the distribution of the two values were indistinguishable (p > 0.8, Wilcoxon Rank Sum test), and they were highly correlated (Pearson’s R² > 0.99) (figure SI-1).

We also tested whether the variability in the concentration distributions changed after fire by using the CRᵥCV. This analysis focused on a smaller subset of the data (table SI-3) since all sites did not have adequate data to reliably estimate variance. The variability in concentrations increased for ~60%–70% of the sites for NO₃⁻, NH₄⁺ and TN, but increased for 40%–60% of sites for DOC, PO₄³⁻, TP, and TSS. For NO₃⁻, NH₄⁺, and TN, there was a median 1.2–1.3-fold increase in CV post-fire, while PO₄³⁻ was the only parameter with CRᵥCV approximately 1 (figure 4(b)). We tested whether CRᵥCV and CRₘ for
each parameter were correlated (figure SI-2). In log-space, the correlation was positive and significant for NO$_3^-$ ($p = 0.05$, $R^2 = 0.08$), NH$_4^+$ ($p = 0.003$, $R^2 = 0.38$), and DOC ($p = 0.03$, $R^2 = 0.33$), suggesting increases in mean concentration also corresponded to increases in concentration variability.

### 3.3. Co-variation between elemental cycles in burned watersheds

We then analyzed relationships between the CR$_M$ values of the various elements to understand how biogeochemical cycles interact post fire. Here, we focused only on a subset of the total dataset where data from multiple constituents was available (63 burned sites). The most data existed for sites co-measuring NO$_3^-$–TP (30), then by NO$_3^-$–TN (27), NO$_3^-$–NH$_4^+$ (26), TN–TP (23), NO$_3^-$–TSS (22), and TN–TSS (21). We found that constituents generally increased together after fire (figure 5), and the CR$_M$ values of multiple parameters were significantly correlated (figure 5 and table SI-5). The most significant positive correlations (assessed by KRC and $\tau$) were observed between TP and PO$_4^{3-}$ CRs (slope = 0.30, KRC $p = 0.07$, $\tau = 0.62$), and TN and NO$_3^-$ CRs (slope = 0.36, KRC $p = 0.01$, $\tau = 0.36$). The positive relationship between the dissolved and total N and P species suggests that similar source and flow pathways impact both dissolved and particulate elemental species. We also observed significant relationships between CR pairs DOC–TN (KRC $p < 0.01$, $\tau = 0.69$) and DOC–PO$_4^{3-}$ (KRC $p = 0.06$, $\tau = 0.73$), highlighting the coupling between the C, N and P cycles. Finally, TSS showed insignificant correlation to all N, P and C species, except DOC (figure 5 and table SI-3). No significant relationship was observed between TSS and TP, contrary to other studies that have documented significant TP–TSS relationships (Froelich 1988, Romanya et al 1994, Reddy et al 1999, Noske et al 2010).

While significant correlations between the CR$_M$ values highlight the coupling of the biogeochemical cycles, the slope of the relationship captures the relative proportions of the changes post-fire. For example, most points in the PO$_4^{3-}$–TP relationships (figure 5) lie below the 1:1 line, implying that PO$_4^{3-}$–TP ratio increases after fire, with a median CR$_M$ value of 1.3 post-fire (figure 6). The results are similar for the NO$_3^-$–TN ratio where 75% of the sites document a value of CR$_M$ > 1 after fire, with over fourfold increases at one site, and a median value for CR$_M$ of 1.4 increase across all sites (figure 6).

Fire contributed to both increases and decreases in the TN:TP ratio across the sites analyzed, with a median CR$_M$ of approximately 1 (IQR 0.57–1.1) (figure 6). The TP:TSS ratio increased after fire, with a median CR$_M$ of 1.3, which we attribute to an increase in the PO$_4^{3-}$–TP ratio (median CR$_M$ = 1.3) and decrease in the PP–TP ratio (CR$_M$ = 0.93) post-fire (figure 6). Finally, we found consistent patterns in the ratios of DOC–NO$_3^-$ and DOC–PO$_4^{3-}$ post-fire, with all sites exhibiting decreases in carbon to nutrient ratios post-fire.

### 3.4. Effect of fire on concentration extremes

While the above analysis focused only on the mean change across the post-fire period, fire can potentially impact concentration extremes and this was visualized using concentration-decile curves. For this analysis we used a subset of the studies that had enough samples: 33 burned sites for NO$_3^-$, and 10–18 for

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**Figure 4.** Change ratios for (a) mean concentration change (CR$_M$) and (b) change in CV (CR$_CV$). A change ratio of 1 indicates no change. Each point is one burned catchment site, with study type represented as shapes (before-after as triangle, control-impact as circle). Boxplots are shown for all before-after and control-impact sites combined. The numbers of sites with data per parameter are included in table SI-3, with means and medians of the change ratios in table SI-4. Stars above each parameter indicate that the population of change ratios has a mean significantly ($p < 0.05$) different from 1 (t-test performed on the log of change ratios).
Figure 5. Comparison of CR\textsubscript{M} for pairs of constituents between burned and reference conditions. There is one point for each burned-reference pair. CR\textsubscript{M} = 1 indicates no change. In each subplot, the black dashed 1-to-1 line is drawn. Kendall’s rank correlation was measured for each relationship, and significant relationships (\(p < 0.10\); table SI-5) are shown with a star in the upper right of each subplot. For all data (including NH\textsubscript{4}\textsuperscript{+} and DON) see table SI-5. The upper right inset shows data availability for pairs of parameters.

TSS, TN, TP, DOC, NH\textsubscript{4}\textsuperscript{+}, and PO\textsubscript{4}\textsuperscript{3–}. The dNCs were aggregated across all sites to evaluate the effect of fire on concentration extremes (figure 7). We find the ‘hockey stick’ pattern that was apparent at a single site (figure 2) to be apparent for almost all parameters, and across all sites (figure SI-3 for all sites). We find TSS to have the most dramatic effect, with the tenth decile concentrations increasing six times more than the mean increase across all sites, while the deciles lower than eight all recorded increases less than the mean increase. Again, this suggests that for all parameters the vast majority of the time, absolute changes (dAC) at high deciles (7–10) drive the magnitude of the site-specific change in the mean concentrations (AC). Looking at low-decile changes, values are either very close to zero or sometimes negative. This suggests that during periods when an unburned catchment would experience low concentrations, little change is seen during the same periods in burned catchments. More extreme behavior is observed at the higher deciles where the median 10th decile change for TSS is 6 times the average increase in TSS concentration, highlighting that the extremes in the concentration distribution show greater change in burned catchments. Finally, it is important to note that there is significant spatial variability between the sites, but the ‘hockey stick’ persists across almost all sites (figure SI-3). These documented increases in concentration extremes are important for drinking water treatment operators that have to plan for extremes in flow and concentrations after fire (Hohner et al 2019).

One challenge in analyzing these data was the wide range in effect sizes, characterized as either dAC or decile change ratios (dCRs; figure SI-4). The normalized metric dNC significantly compressed variability, highlighting the importance of changes
Figure 6. Change ratios (CRM) for the nutrient ratios. A value greater than 1 indicates that the ratio of the two elements has increased post-fire compared to the reference. Data is presented as in figure 4.

Figure 7. Following the example in figure 2, for each burned site with sufficient data to calculate deciles, the decile normalized change (dNC) was calculated as the ratio of decile change (dAC) over total change (AC). For each parameter, the median value of dNC is shown with error bars representing the interquartile range. For all data, see figure SI-3.

at high concentrations. That said, the use of CRs throughout the rest of this study highlights benefits and some limitations of these metrics. CR can be highly influenced by small denominators in the fraction, thus inflating the metrics. For example, dCR values show indiscernible patterns across deciles (figure SI-4), because as you decrease in decile, the concentration decreases and the dCR metric inflates. While different metric certainly have different uses, we are confident that the dNC provides a useful comparison of the magnitude of decile changes relative to total changes.
3.5. Attribution analysis

The results of the attribution analysis were challenging to interpret, given the limited information available at the individual sites, and the high variability between the sites. CRM for NO$_3^-$ was negatively correlated with catchment area (Kendall’s rank correlation tau (Krct), $p < 0.01$, $n = 55$), possibly indicating dilution effects at larger catchment sizes. While CRM for NO$_3^-$ did not have a significant relationship with percent burned, catchment size was negatively correlated with areal burn percent (Krct, $p = 0.04$; figure SI-5). Smaller catchments have more prescribed fires (KWt, $p < 0.001$), which possibly contributes to the higher burn percent. In contrast to the individual correlations, the conditional inference tree analysis highlighted a breakpoint predicted by burn type for CRM for NO$_3^-$ (prescribed, $n = 7$, mean 29.5; natural, $n = 64$, mean 4.7; $p = 0.015$). The relationships were also not consistent across the spectrum of solutes, with CRM for TP being positively correlated with catchment area (Krct, $p = 0.03$, $n = 29$), while CRM for TSS had a significant correlation with areal burn percent (Krct, $p = 0.02$, $n = 23$). Overall, our attribution analysis (figure SI-6) was not able to identify any common trends among variables. Part of the challenge in identifying drivers of nutrient changes are the confounding effects of single perturbation events from long-term nutrient budget alterations. A recent analysis by Crandall et al. (2021) compared pristine and anthropogenically impacted burned watersheds in Utah, USA. They conclude that 'direct human impact, not megafire, is the primary threat to aquatic ecosystems in semiarid ecosystems.' A recent isotope-tracing study (Abbott et al. 2021) in burned Arctic watersheds highlighted that the isotopic signature of exported nitrate was similar to that in unburned watersheds, highlighting the ability of fire to mobilize existing nutrient stocks. Other analyses have focused on a wider range of variables, such as stream temperature, that have been affected by fire (Rhoades et al. 2011, Subiza et al. 2018, Kichigina and Bilichenko 2019). These kinds of analyses will be improved in the future as more high temporal and spatial resolution water quality data are combined with detailed catchment characteristics from satellites and other sources.

4. Summary and conclusions

In the present work, we have used a meta-analyses approach to quantify the effect of fire on nitrogen, phosphorus, carbon species, as well as suspended sediments in streams draining burned watersheds. We identified 34 studies, including data from 81 burned and 40 reference catchments. We found that while 31 studies measured flow, almost none had data in an accessible format for use in our metaanalysis. We acknowledge that our sites and findings are primarily relevant to North America, and future extensions of this work should include a broader geographical distribution of sites. With increasing incidences of wildfires across the world, the number of studies exploring wildfire effects are increasing which will allow future meta-analysis studies to be more geographically diverse. For water quality parameters, the most data were available for nitrogen (67 as NO$_3^-$, 30 as NH$_4^+$), followed by phosphorus (41 as PO$_4^{3-}$, 20 as TP) and suspended sediments (26 sites). Studies that looked at DOC and DON were more limited. Most studies focused on one or two elements, thus making it challenging to understand the coupling of elemental cycles. For example, only ~40% of NO$_3^-$ sites were also sampled for TSS or TP. Finally, we found that most sites (>92%) recorded data for five years or fewer, severely limiting our ability in this study to evaluate recovery of streams post-fire.

Overall, we found that concentrations of nutrients and sediments increased after fire (measured as the change ratio of mean concentration CRM), with the largest increases observed for NO$_3^-$ (median CRM = 2.1), TP (CRM = 1.9), and NH$_4^+$ (CRM = 1.3), with smaller increases for PO$_4^{3-}$, TN, DOC, and TSS. When exploring the coupling of nutrient cycles, we found that increases in one parameter generally predicted an increase in another parameter. The proportion of inorganic nitrogen and phosphorus (NO$_3^-$–TN and PO$_4^{3-}$–TP) increased in 74% and 62% of sites post-fire, with median CRM values of 1.4 and 1.3, respectively. We also found that DOC–NO$_3^-$ and DOC–PO$_4^{3-}$ ratios decreased post fire at almost all sites. Increase in dissolved inorganic nutrients in the immediate aftermath of the fire can be attributed to a variety of reasons, including: (a) subsurface release due to suppressed nutrient uptake by terrestrial biota (Hauer and Spencer 1998, Ranalli 2004, Certini 2005), (b) ash deposits from the fire as a source of dissolved organic and inorganic nutrients (Earl and Blinn 2003, Spencer et al. 2003, Rhoades et al. 2011, Revchuk and Suffet 2014, Cawley et al. 2016, 2018, Brito et al. 2021), and (c) inhibition of in-stream processes, such as NO$_3^-$ uptake, due to lower DOC export and a more aromatic DOC signature from burned watersheds (Rodriguez-Cardona et al. 2020). Indeed, we find a decrease in DOC–NO$_3^-$ and DOC–PO$_4^{3-}$ ratios after fire, which possibly inhibits NO$_3^-$ uptake in the streams draining the forested watersheds. Anderson et al. (2002) have suggested that shifts in nutrient ratios including N:P and DOC:DON caused shifts in freshwater plankton species composition. The changes in these ratios are important to the downstream ecosystem and potential for algal growth. Dissolved forms of the nutrients are more bioavailable, and thus might pose greater eutrophication risk downstream. Much is yet to be learned about these altered ratios in post-fire landscapes.
Finally, we explored the effect of fire on concentration extremes, and found that concentration increases were greater at the higher concentration deciles, compared to the lower concentration deciles, creating a hockey-stick-like response. The increase in concentration extremes in the post-fire period has significant implications with respect to water treatability for downgradient communities that might be using the river as a water source. It is thus recommended that studies place special emphasis on capturing high concentration events that often co-occur with high flow events. Our meta-analysis highlights the need for continued long term monitoring of water quality in post-fire landscapes, along with the exploration of covariation between multiple elemental cycles and storm driven responses in concentration extremes. Increased data-sharing of existing and future datasets will greatly aid future analyses of fire effects on water quality, especially as more studies from around the globe are published on this topic. Such advances in the field will help managers plan for water treatment challenges arising from fires in forested source waters. Stream corridors are complex eco-hydrological systems, and disturbance regimes add even more complexity as we seek to understand the effects of short- and long-term changes across the landscape. Fire has been a natural part of this system for millennia, and there is much work left to do to understand the impacts of fire to both natural systems and our human infrastructure.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: www.hydroshare.org/resource/537dc5206d584625b0fd286a66b872de/.

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