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Persistent and lagged effects of fire on stream solutes linked to intermittent precipitation in arid lands

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Abstract Increased occurrence, size, and intensity of fire result in significant but variable changes to hydrology and material retention in watersheds with concomitant effects on stream biogeochemistry. In arid regions, seasonal and episodic precipitation results in intermittency in flows connecting watersheds to recipient streams that can delay the effects of fire on stream chemistry. We investigated how the spatial extent of fire within watersheds interacts with variability in amount and timing of precipitation to influence stream chemistry of three forested, montane watersheds in a monsoonal climate and four coastal, chaparral watersheds in a Mediterranean climate. We applied state-space models to estimate effects of precipitation, fire, and their interaction on stream chemistry up to five years following fire using 15 + years of monthly observations. Precipitation alone diluted specific conductance and flushed nitrate and phosphate to Mediterranean streams. Fire had positive and negative effects on specific conductance in both climates, whereas ammonium and nitrate concentrations

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increased following fire in Mediterranean streams. Fire and precipitation had positive interactive effects on specific conductance in monsoonal streams and on ammonium in Mediterranean streams. In most cases, the effects of fire and its interaction with precipitation persisted or were lagged 2–5 years. These results suggest that precipitation influences the timing and intensity of the effects of fire on stream solute dynamics in aridland watersheds, but these responses vary by climate, solute, and watershed characteristics. Time series models were applied to data from long-term monitoring that included observations before and after fire, yielding estimated effects of fire on aridland stream chemistry. This statistical approach captured effects of local-scale temporal variation, including delayed responses to fire, and may be used to reduce uncertainty in predicted responses of water quality under changing fire and precipitation regimes of arid lands.

Keywords Fire · Arid lands · Precipitation · Stream · Specific conductance · Nutrients

Introduction

Fire activity in the western U.S. has increased in extent and intensity in the past several decades (Holden et al. 2018; Senande-Rivera et al. 2022; Williams et al. 2022). Land cover change, fire suppression, and changing climate doubled the area burned in the region between 1984 and 2015 (Abatzoglou and Williams 2016). To date, studies of ecosystem recovery from fire in the western U.S. have focused on terrestrial ecosystems in mesic, forested regions (Abatzoglou and Williams 2016; Holden et al. 2018). Arid to sub-humid shrubland and forested ecosystems (aridity index [precipitation/potential evapotranspiration] < 0.65, Cherlet et al. 2018) are also prone to fire, and future projections of fire extent in these ecosystems are uncertain (Senande-Rivera et al. 2022). In the arid western U.S., streams and rivers serve as a vital habitat and water source in otherwise water-limited regions. However, fires cause declines in water quality that propagate downstream (Ball et al. 2021; Paul et al. 2022).

Due to intermittency in the flowpaths connecting uplands to streams in arid lands, precipitation patterns influence the delivery of combustion products and materials accumulated post-fire to streams. The outcome of this interaction is particularly difficult to predict in arid lands, where precipitation is episodic, seasonal, and variable among years (Guirguis and Avissar 2008). Episodic precipitation in arid lands can cause flash floods that transport large pulses of solutes and particulates of variable timing and magnitude, depending on antecedent precipitation and storm size (Harms and Grimm 2010; Sherson et al. 2015; Warrick et al. 2015). Asynchrony between fire and precipitation in arid regions, post-fire terrestrial processing of materials derived from direct or indirect effects of combustion, or aeolian transport from burned areas might limit transport of materials from burned areas to aridland streams (Earl and Blinn 2003; Goodridge et al. 2018). Alternatively, overland flows during storms might facilitate rapid delivery of combustion products accumulated post-fire (Raoelison et al. 2023). Beyond the timescale of storms or seasonal precipitation, post-fire recovery of vegetation can influence recovery of water quality in aridland streams but also depends on local precipitation regime (Verkaik et al. 2013; Goodridge et al. 2018; Paul et al. 2022). Resolving the time scales of interactions between fire and precipitation are necessary to disentangle the effects of hydroclimate on resulting stream chemistry.

Fire influences the transport of materials from upland burns to streams. For example, combustion of vegetation reduces evapotranspiration, causing increased flow along shallower flowpaths (Rey et al. 2023). Greater spatial extent of fire is correlated with longer hydrologic recovery times of post-fire streamflow (Hampton and Basu 2022). Fire also increases soil hydrophobicity, reduces ground cover, and creates more readily transported particulate material, conditions that may cause greater runoff and erosion during storms (Shakesby et al. 2000). In the Mediterranean region of southern California, fire season has historically been from approximately June through October (Dong et al. 2022), and the majority of annual precipitation occurs as rain in the following months (December–March) with corresponding peaks in nutrient export during post-fire storms (Coombs and Melack 2013; Aguilera and Melack 2018b; Goodridge et al. 2018). In contrast, fire season in monsoonal regions of the arid western U.S. is in spring (May–June), and these regions receive approximately half of their annual precipitation in

winter (before fire season) and half during late-summer monsoon storms (July–October, Arizpe et al. 2020). In the monsoonal region of New Mexico, fire may have variable effects on water quality within a single watershed; nutrient concentrations and specific conductance increase in 2nd to 4th order streams during summer storms following fire (Reale et al. 2015; Sherson et al. 2015), but specific conductance displays patterns of both significant dilution and flushing in the 7th order river downstream (Dahm et al. 2015).

Although fire frequency and extent have been intensifying across the western U.S. over the past several decades, research seldom addresses effects on water quality specifically in arid lands, where watershed biogeochemistry is strongly coupled to the hydrologic regime. Whereas previous analyses of fire effects on water quality have focused on annual concentrations (Rust et al. 2019), monthly temporal variation allows us to quantify interactive effects of fire and precipitation on watershed biogeochemistry. Here, using 15 years of monthly data, we developed a novel framework that simultaneously considers the effect of precipitation regime, fire regime, their interactions, and the lag effects on water quality in arid lands. Such a framework can be broadly applicable to other watersheds and is especially timely under climate change, which has been significantly altering both fire and precipitation regimes.

Because of the variable nature of precipitation in arid lands, we predicted that the interaction between fire and precipitation would have a strong effect on changes in stream chemistry, but that the magnitude of this effect would vary depending on interactions between hydroclimate and watershed characteristics. We also predicted that more reactive solutes (e.g., nutrients) would respond more strongly to fire than specific conductance but for a shorter duration as upland vegetation recovered and biological retention increased following fire. Finally, we predicted that these effects would persist beyond the first year after fire since precipitation in these watersheds is episodic and variable at an annual scale, and therefore combustion products may persist on the landscape for long periods before being transported into streams. Similar to the magnitude of these effects, we predicted that their duration would be mediated by local hydroclimate and watershed characteristics. In this study, we consider the effects of fire, precipitation, and their interaction on aridland stream biogeochemistry and provide an analytical framework that can be applied broadly to advance our understanding of post-fire effects on water quality in water-scarce regions.

Methods

We analyzed monthly time-series (15 + years) from seven watersheds in two arid regions of the western U.S. (Mediterranean and monsoonal) to quantify the effects of precipitation, fire, and their interaction on changes in stream water quality. Each of the watersheds burned 1–2 times during the study period. We define the interaction of fire and precipitation as the period following a fire during which precipitation (both rain and snow) falls on the burned landscape and can transport combustion products through both surface and subsurface flowpaths.

Study sites

We assembled data from four streams in Santa Barbara County, California, U.S.A. and three streams in Valles Caldera National Preserve, New Mexico, U.S.A. (Fig. 1). The streams in California (Arroyo Burro, Gaviota, Arroyo Hondo, and Rattlesnake) are located in the Santa Ynez Mountains, draining south into the Santa Barbara Channel, and were monitored for discharge and streamwater chemistry from the early 2000s until 2018 as part of the Santa Barbara Coastal Long-Term Ecological Research (SBC LTER) program (LTER and Melack 2020). Watershed sizes range from 6 to 50 km^2, and maximum elevations range from 865 to 1416 m (Aguilera and Melack 2018a). Climate of the Santa Barbara region is characterized as Mediterranean, with warm, dry summers and cool, wet winters, during which 80% of annual rainfall typically occurs (Aguilera and Melack 2018a). Land use in the watersheds ranges from undeveloped (e.g., Arroyo Hondo [HO00]) to urban (e.g., Arroyo Burro [AB00]). In undeveloped regions, land cover consists primarily of grassland (e.g., *Bromus* spp.), coastal sage scrub (e.g., *Artemisia californica)*, or chaparral (e.g., *Adenostoma fasciculatum*) vegetation (Keeley and Davis 2007; Hanan et al. 2016; Aguilera and Melack 2018a). During the time period examined in this study (2002–2018), three fires affected the watersheds (Table 1, U.S. Geological Survey and U.S. Department of Agriculture 2022).

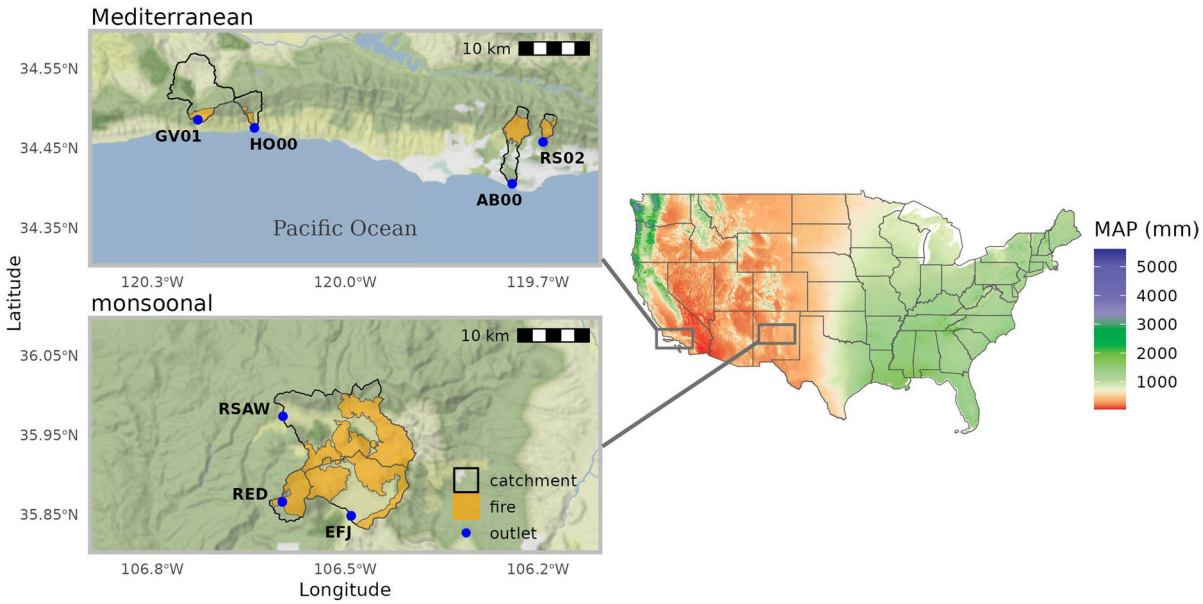


Fig. 1 Map of conterminous United States colored by mean annual precipitation (MAP) as an indicator of aridity with insets for the arid regions included in this study. Top inset: Mediterranean Santa Barbara (SB), California watersheds (delineated in black), fire perimeters (shaded in yellow, Table 1), and stream sampling locations (blue points; AB00 = Arroyo Burro, GV01 = Gaviota, HO00 = Arroyo Hondo, RS02 = Rattlesnake). Bottom inset: Monsoonal Valles Caldera (VC), New Mexico watersheds (EFJ = East Fork Jemez, RED = Redondo, RSAW = Rio San Antonio West)

Table 1 Watershed characteristics for each of the study sites and fire characteristics for each of the corresponding fires that occurred within a watershed during the period of analysis

Site	Predominant vegetation cover	Fire name	Date of ignition	% of Watershed burned	Proximity to fire perimeter (m)
Mediterranean streams					
AB00	Shrubland, irrigated grass, agriculture[1]	Jesusita	May 5, 2009	45.5	6610
GV01	Grassland, riparian, shrubland[1]	Gaviota	June 5, 2004	8.8	0
HO00	Shrubland, riparian, grassland[1]	Gaviota	June 5, 2004	17.1	0
RS02	Shrubland, riparian,	Tea	November 13, 2008	9.3	0
	irrigated grass[1]	Jesusita	May 5, 2009	68.4	0
Monsoonal streams					
EFJ	Mixed conifer forest, montane grassland, wet meadow[2]	Las Conchas	June 26, 2011	37	2290
		Thompson Ridge	May 31, 2013	21.7	4840
RED	Mixed conifer forest, montane shrubland, ponderosa pine forest[2]	Thompson Ridge	May 31, 2013	93.5	0
RSAW	Mixed conifer forest, montane grassland, wet meadow[2]	Las Conchas	June 26, 2011	42.8	9380
		Thompson Ridge	May 31, 2013	7.8	10,300

Mediterranean watershed vegetation information from Aguilera and Melack (2018b) and monsoonal watershed vegetation information from Muldavin et al. (2006). Proximity to fire perimeter is defined as the channel length from the intersection of the fire perimeter with the nearest stream line to the sampling location (see Supplementary Methods)

[1]Aguilera and Melack 2018b; [2]Muldavin et al. 2006

All three streams in New Mexico (East Fork Jemez River, Redondo Creek, and West Rio San Antonio) are located in the Valles Caldera National Preserve, which coordinates a network of stream and meteorological monitoring stations in cooperation with the National Park Service, the University of New Mexico, the Western Regional Climate Center, and the Jemez River Basin Critical Zone Observatory (Chorover et al. 2011). The Valles Caldera is an expansive meadow valley with several resurgent domes (elevated areas) that are drained by headwater streams, over an elevation range of 2300 to 3432 m (Heiken et al. 1990). Vegetation consists of high-elevation montane grassland and wetlands within the low-gradient valley floor, and forests of ponderosa pine (*Pinus ponderosa*), fir (*Abies concolor, Abies lasiocarpa var. arizonica,* and *Pseudotsuga menziesii*), spruce (*Picea pungens* and *Picea engelmannii*), and aspen (*Populus tremuloides*) on slopes. The Valles Caldera is characterized by a monsoonal climate, with 50% of annual precipitation typically occurring as rain between July and September and the other 50% as snow and contributing to runoff during spring snowmelt (Sherson et al. 2015). During the period of this study (2005–2021), two major fires occurred in these watersheds (Table 1, U.S. Geological Survey and U.S. Department of Agriculture 2022).

Data collection and preparation

To quantify the long-term effects of fire on stream chemistry, we analyzed time series of chemistry, cumulative monthly precipitation, and percentage of the watershed burned (Table 1, Supplementary Table 1). For the four watersheds in Santa Barbara with a Mediterranean climate (hereafter referred to as Mediterranean streams), ammonium (NH_4^+), nitrate (NO_3^-), and phosphate (PO_4^{3-}) concentrations and specific conductance were available at hourly to biweekly frequency for 2002–2018 (LTER and Melack 2020). Nutrient concentrations were transformed to analyze volume-weighted mean concentrations to account for variation in discharge (Eq. S1). Dissolved nutrients and specific conductance are commonly reported water quality measurements, with nutrient data providing information about individual reactive dissolved species and specific conductance data representing an aggregated measure of stream chemistry, including all dissolved ions. Specific conductance has been shown to indicate ash and changes in hydrology (Mishra et al. 2021) while nutrients can indicate changes in these as well as biotic uptake and transformation (Likens et al. 1970). Precipitation data were assembled from SBC LTER and Santa Barbara County Flood Control District (https://sbclter.msi.ucsb.edu/data/catalog/). Discharge data were assembled from SBC LTER and the U.S. Geological Survey (USGS; U. S. Geological Survey 2022). For the three forested, montane watersheds in the Valles Caldera with a monsoonal climate (hereafter referred to as monsoonal streams), specific conductance and precipitation were available for 2005–2020. A combination of discrete (approximately monthly) and continuous (15-min interval) observations of specific conductance were collected by the Valles Caldera National Preserve from 2005–2018 and in cooperation with the Crossey Lab at University of New Mexico from 2018–2020, from whom the data was obtained (Valles Caldera National Preserve, University of New Mexico). Precipitation data (10-min interval) were assembled from six stations maintained by the Western Regional Climate Center and matched to closest streams (Western Regional Climate Center 2021); precipitation as snow was included as falling snow that was melted and measured within heated tipping buckets and is not distinguished from rain (Daly et al. 2021). See Supplementary Information for additional information regarding sample collection, processing, and reporting.

To determine the percentage of each watershed burned during the fires, we first delineated the contributing watershed area to each stream sampling location using mapping services provided by the USGS StreamStats program (U.S. Geological Survey 2019). We used the *sf* package for R (Pebesma 2018) with fire perimeters (Monitoring Trends in Burn Severity, MTBS, program, Eidenshink et al. 2007; U.S. Geological Survey and U.S. Department of Agriculture 2022) to calculate the areal extent of fires within each study watershed. Using these estimates, we constructed a monthly, 15-year time series of percentage of the watershed burned for each site. We used the percent of the watershed burned as the measure of fire extent rather than fire severity (i.e., low, medium, and high; Eidenshink et al. 2007) due to the uncertainty surrounding estimates of fire severity at high temporal and spatial resolutions. In addition, burn severity may be overestimated in arid regions.

This bias is a result of quantifying aboveground biomass removal based on vegetation height in regions where vegetation is dominated by short shrubs that are prone to complete consumption during fire (Gale and Cary 2022).

The modeling approach described below requires data at regular intervals across the time series; thus, data across all Mediterranean and monsoonal streams were averaged to calendar month intervals, the shortest regular interval for which data were available over the full 15-year duration of the study (see Supplementary Information). Furthermore, prior to model fitting, all stream chemistry and covariate data were logarithmically transformed and scaled to standard deviations from the mean so that estimated effect sizes could be directly compared across stream sites and hydroclimate regions.

Multivariate state-space models

We used multivariate autoregressive state-space models (MARSS) to examine the interactive effect of fire and precipitation on stream chemistry. We selected this approach because it incorporates variable time lags and multiple interacting independent variables, while remaining easily interpretable because of its basis in multiple linear regression. Briefly, state-space models combine (1) an observation model that incorporates direct measurements of temporal variation in the state of a system with (2) a process model that includes variation due to stochastic processes and represents the unobserved state of the environment (Auger-Méthé et al. 2021).

The MARSS observation model, which includes the stream chemistry data, takes the form:

$$y_t = x_t + v_t \quad (1)$$

where y_t is a $j \times 1$ vector of the observed stream chemistry measurements in month t ($t = 1, 2, 3 \ldots 181$) for each of the j streams ($j = 7$ or 4) considered in a particular analysis, x_t is a $j \times 1$ vector of the unobserved states (see Eq. 2), and v_t is a $j \times 1$ vector of observation errors which are $normal(0, R)$ where R is a $j \times j$ matrix of the covariance of observation errors between streams, which was structured to share covariance within but not across regions (see Supplementary Tables 4 and 5).

The MARSS process model, which contains the environmental covariate data, takes the form:

$$x_t = x_{t-1} + Cc_t + w_t \quad (2)$$

where x_t is a $j \times 1$ vector of the unobserved states of stream chemistry in month t, and x_{t-1} is a $j \times 1$ vector of the previous month's state. C is a $j \times k$ matrix that contains the effects of fire, precipitation, and their interaction (see Supplementary Table 6) where k is the product of j sites and the three environmental drivers investigated. Standardized measurements of these drivers (i.e., percent of the watershed burned, cumulative monthly precipitation, and the product of these values) are contained in the $k \times 1$ vector c_t. In addition, w_t are process errors that are represented by a multivariate normal distribution, $normal(0, Q)$, where Q is a $j \times j$ matrix of the covariance of process errors between streams (see Supplementary Tables 7–9). We considered different Q matrix structures per solute in which process errors covaried among all sites, process errors covaried only by climate region, or process errors did not covary in any sites. In all models, dynamics of each stream were modeled as a unique state in a single, multi-state model. This multi-state structure was specified by the Z matrix of $j \times j$ dimensions that mapped the observations from each stream to the unique states. We did not consider distinct states by using different Z matrix structures, because there is no solution when covariate time series outnumber states (i.e., Z must equal j or the number of streams in our model structure).

Specific conductance or one of the solute concentrations (i.e., ammonium, nitrate, or phosphate) were response variables in separate candidate MARSS models. Models of specific conductance included both monsoonal and Mediterranean streams (n = 7 streams total), whereas nutrient data were available only for Mediterranean streams (n = 4 streams total, Supplementary Table 1). For each solute, we built six separate MARSS models to investigate different durations of estimated fire effects (hereafter fire-effect durations, Fig. 2) and different versions of those six models to determine the most parsimonious error covariance structure (Q). We were unable to include all fire-effect durations in a single model because limited data caused failure of model convergence. Unlike many other time-series approaches, MARSS models estimate

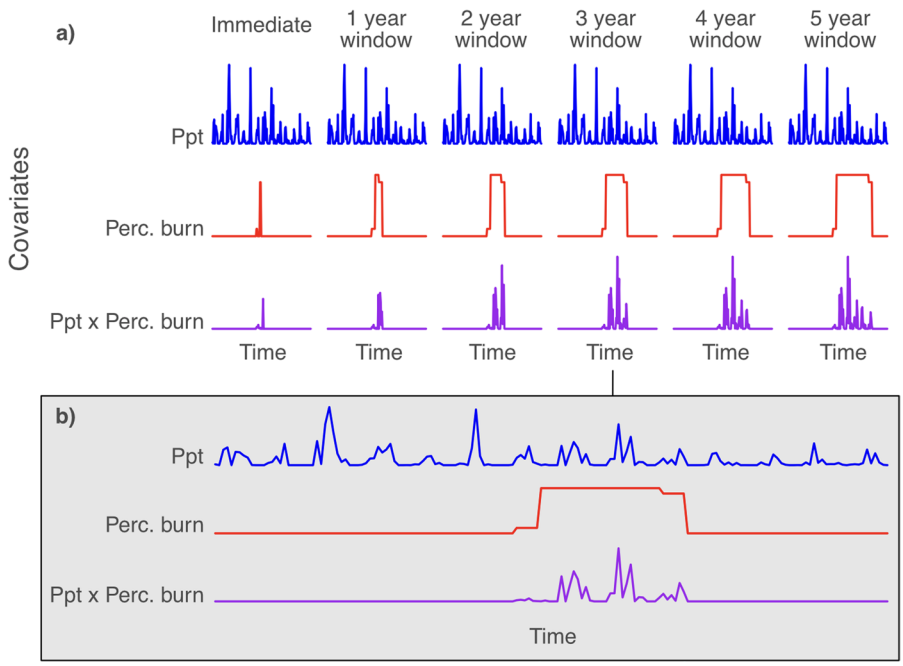


Fig. 2 Example time series (monthly resolution) of covariates used in multivariate autoregressive state-space (MARSS) models: precipitation (Ppt), burned area (Perc. Burn), and their interaction (Ppt x Perc. Burn). **a** Six models were constructed that vary only in the duration of estimated fire effects identified by the column labels. The immediate window included Perc. Burn in the two months following fire and Ppt x Perc. Burn over six months following fire. **b** Detailed view of covariates for the 3-year fire effect depicting how values of the Ppt x Perc. Burn interaction in the absence of fire or precipitation reduce the magnitude of the interaction effect. The step-shaped effect of Perc. Burn is due to two fires, one small and another that burned the majority of the example watershed, Rattlesnake Creek (RS02)

both observation error and process error, which makes them robust to missing observations. In addition, both forms of error are allowed to covary among combinations of sites, and final model forms were selected according to the best fit to the data. This structure allowed for spatially-grouped errors, which was ideal for our multi-site and multi-region dataset. In total, 18 MARSS models consisting of 6 fire-effect durations with 3 possible Q matrices were fit to the specific conductance data and 12 MARSS models consisting of 6 fire-effect durations with 2 possible Q matrices were fit to each nutrient using the *MARSS* package (Holmes et al. 2021) in R (version 4.2.2, Supplementary Table 3).

Fire-effect durations were constructed as a monthly time series of percent of the watershed burned with duration of two months ("immediate" in Fig. 2a), one year, two years, three years, four years, and five years post-fire, setting all other values in the time series during which fire effects were not present to zero. The "immediate" fire-effect duration was selected to include fire ignition and containment (i.e., no further expansion). The interaction effect in the "immediate" duration model spanned six months following the fire ignition date and was based on the longest period of time between a recorded fire and subsequent storm at all seven sites. The remaining fire-effect durations (up to five years post-fire) were chosen based on hypothesized time frames of responses to fires in streams (Verkaik et al. 2013; Raoelison et al. 2023). If multiple fires occurred at a site (Table 1) and their fire-effect durations overlapped, we included the percent watershed burned as an additive value. The effect sizes for fire quantify the standard-deviation change in stream chemistry between pre- and post-fire periods when one fire occurred, or the standard-deviation change in stream chemistry resulting from a one standard deviation increase in burned area for sites with multiple fires during the study period. The interactive effect of fire and precipitation is interpreted as the standard-deviation

change in stream chemistry expected in response to one standard deviation increase in the product of burned area and precipitation.

Following model fitting, we used Akaike's Information Criterion adjusted for small sample sizes (AICc, Brewer et al. 2016) to compare each model to a null model with no covariates to ensure model structures containing covariates explained more variation in stream solutes. All models were evaluated further by using the autoplot.marssMLE function in the *MARSS* package (Holmes et al. 2021) to ensure residuals did not contain temporal patterns or autocorrelation and were normally distributed; only sites that passed these criteria are included in the analysis. We also used AICc values to select the most parsimonious Q matrix structure (across all fire-effect durations), and the results from the models with the Q matrix structure that produced the lowest AICc value are presented in the figures. To account for the multiple tests imposed on the same data (i.e., six separate structures examining fire-effect duration) and so as not to overreport significance of effect sizes, we present estimated effects with both 95 and 99% bootstrapped confidence intervals. We identify 95% confidence intervals that do not overlap zero as weak effects and 99% confidence intervals that do not overlap zero as strong positive or negative effects. Additional details regarding model construction and all resulting R scripts and model fits may be found at https://doi.org/10.5281/zenodo.11199122.

Results

In Mediterranean watersheds, the majority of precipitation arrived as rain December through March (mean cumulative monthly precipitation = 102 mm) with little to no precipitation between June and September (mean cumulative monthly precipitation = 2 mm, Supplementary Fig. 1). Precipitation was bimodal at the monsoonal sites, with precipitation occurring during late summer in July through September (mean cumulative monthly precipitation = 71 mm) and in winter as snow (mean cumulative monthly precipitation = 56 mm, Supplementary Fig. 1). Monthly cumulative precipitation was greater, on average, but less variable temporally at the monsoonal sites, with a median of 38 mm (range 0–480) compared to median of 5 mm (range 0–1,102) at the Mediterranean sites.

Temporal variation in specific conductance was related to fire, precipitation, or their interaction but the relative importance of these effects varied by climate region. Measured specific conductance values were greater in Mediterranean streams (median = 1,230, range 342–3774 µS cm^{-1}) than in monsoonal streams (median = 98, range 42–223 µS cm^{-1}; Supplementary Fig. 2). Temporal variation in specific conductance was also greater in Mediterranean streams (standard deviation = 622 vs. 30 µS cm^{-1} in Mediterranean and monsoonal streams, respectively). Across all fire-effect durations, the most parsimonious model for specific conductance included process error that co-varied by region (Mediterranean vs. monsoonal). Precipitation alone had the strongest effect on specific conductance in Mediterranean streams, causing significant dilution (Fig. 3). In monsoonal streams, precipitation alone had a negligible effect on specific conductance. Fire alone had variable effects on specific conductance among Mediterranean streams, with a negative effect occurring in GV01 and a positive effect appearing in AB00 4 years post-fire. The effect of fire on specific conductance also varied across monsoonal streams, with a positive effect detected up to 4 years post-fire in RED and a negative effect 2 years post-fire in RSAW. The interaction between fire and precipitation had positive effects on specific conductance in all monsoonal streams, though the strength and duration varied (Fig. 3); a positive effect appeared only in the first year post-fire in EFJ but appeared immediately and persisted 3 years post-fire in RSAW. Interactive effects of fire and precipitation on specific conductance were minimal in Mediterranean streams, with only a weak negative effect 4 + years post-fire in AB00 (Fig. 3).

In Mediterranean streams, temporal variation in dissolved nutrients (NH_4^+, NO_3^-, PO_4^{3-}) was related to fire, precipitation, or their interaction but the importance of these effects varied by solute. Volume-weighted mean monthly nutrient concentrations ranged from 0.03 to 159 µmol L^{-1} for NH_4^+ (median = 0.2, standard deviation = 8.0 µmol L^{-1}), 0.25 to 590 µmol L^{-1} for NO_3^- (median = 6.17, standard deviation = 45.6 µmol L^{-1}), and 0.15 to 30.0 µmol L^{-1} for PO_4^{3-} (median = 0.8, standard deviation = 3.4 µmol L^{-1}); overall, nutrient concentrations

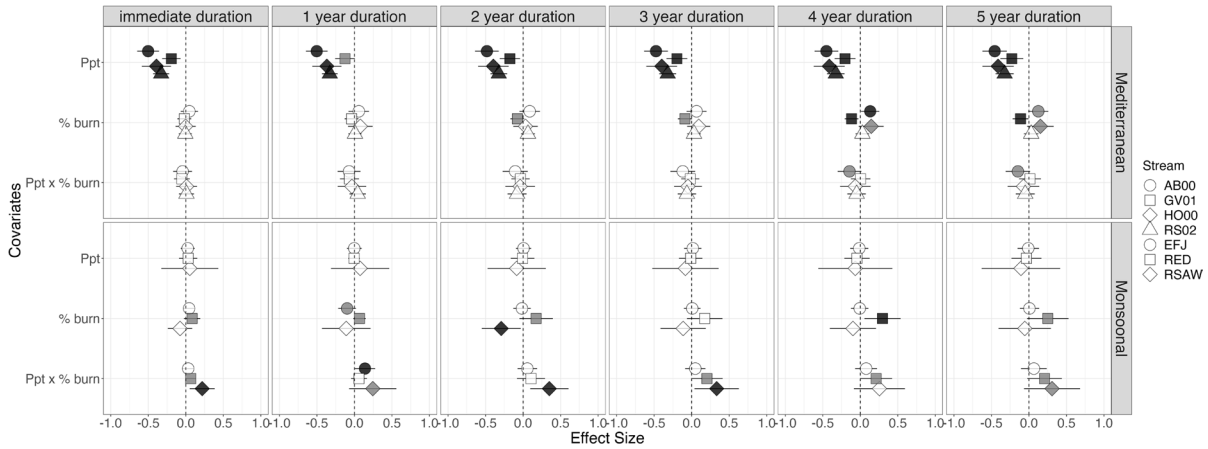


Fig. 3 Multi-year standardized effects of precipitation (Ppt), fire (% burn), and their interaction (Ppt x % burn) on standardized, log-transformed monthly observations of specific conductance in aridland streams. Sites identified as in Fig. 1. Weak effects (95% confidence intervals, CI, that do not overlap zero) are filled in gray, and strong effects (99% CI that do not overlap zero) are filled in black. Error bars depict 99% CI

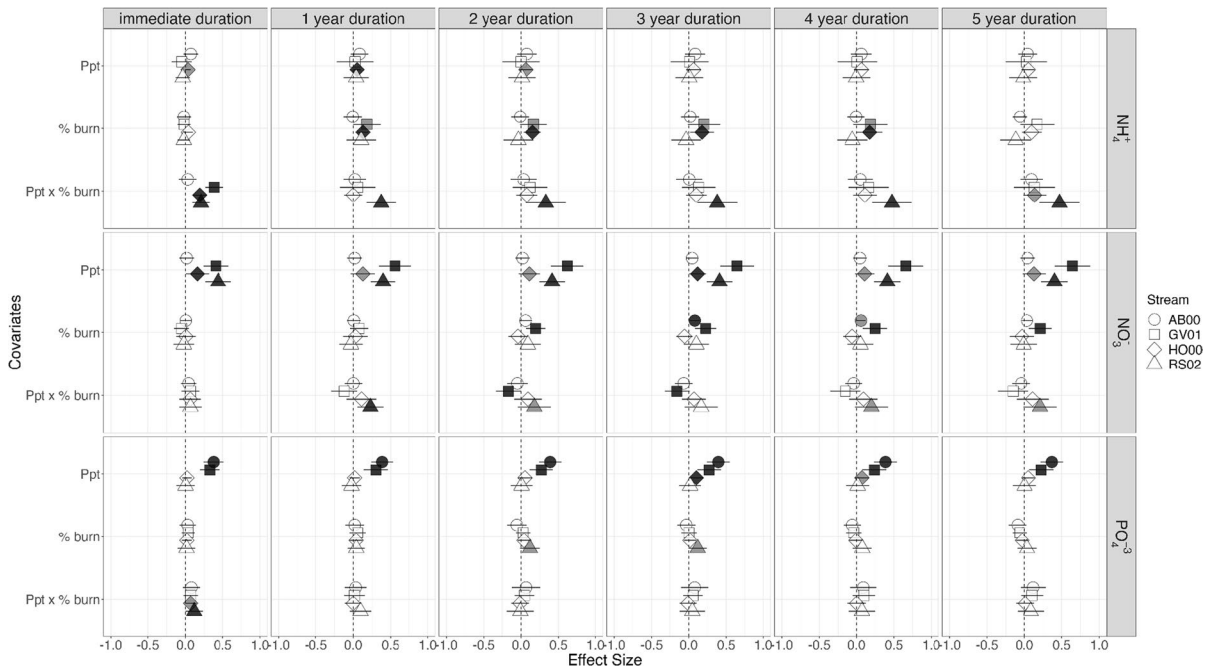


Fig. 4 Multi-year standardized effects of precipitation, fire, and their interaction on standardized, log-transformed monthly observations of volume-weighted NH_4^+, NO_3^-, and PO_4^{3-} estimated in four Mediterranean streams. Sites identified as in Fig. 1. Weak effects (95% confidence intervals, CI, that do not overlap zero) are denoted as gray filled shapes, and strong positive and negative effects (99% CI that do not overlap zero) are denoted as black filled shapes. Error bars depict 99% CI

varied by several orders of magnitude in each of the Mediterranean streams (Supplementary Fig. 3–5). For all fire-effect durations, the most parsimonious MARSS model structure for nutrient concentrations included non-independent estimates of process error that co-varied across all four streams.

Precipitation alone had the strongest effect on NO_3^- and PO_4^{3-} concentrations whereas the interaction effect of fire and precipitation was more strongly correlated with NH_4^+ concentration in Mediterranean streams (Fig. 4). There was a positive effect of precipitation alone on NH_4^+ concentration in only one stream (HO00). Positive effects of fire on NH_4^+ were detected one year following fire and persisted for four years in the same stream (HO00). The interaction between fire and precipitation had a positive effect on NH_4^+, appearing in three streams immediately following the fire (GV01, HO00, and RS02) and persisting up to five years post-fire in one stream (RS02). Precipitation flushed NO_3^- to all streams except AB00. Fire had a lagged positive effect on NO_3^- concentration 3 years post-fire in HO00 and a lagged but persistent effect 2 + years post-fire in GV01. The interaction between fire and precipitation had mixed effects on NO_3^-; one stream displayed a positive effect in the year following the fire (RS02) while another displayed a negative effect 2–3 years post-fire (GV01). Precipitation also flushed PO_4^{3-} to all streams except RS02, and there was a negligible effect of fire on PO_4^{3-} in any stream. Fire and precipitation together had an immediate, positive effect on PO_4^{3-} in one stream (RS02) that did not persist.

Discussion

Autoregressive state-space models supported by 15 years of monthly observations were used to characterize how fire interacts with the timing and amount of precipitation to influence solute concentrations in streams of two aridland regions. In monsoon-influenced streams, fire and precipitation interactively increased specific conductance and the duration of effects indicated that solute concentrations remain elevated for three to five years after fire in these otherwise low-conductivity streams. In most Mediterranean streams, elevated concentrations of inorganic nitrogen (NH_4^+, NO_3^-) after fire suggested that increased supply or transport of nitrogen from the watershed persisted up to five years after fire. Overall, interactive effects of fire and precipitation influenced temporal patterns in transport of materials from burned, aridland watersheds to streams, but the duration and magnitude of these effects varied across climate regions and among watersheds, likely due to contrasts in surface and subsurface flowpaths, proximity to the fire, and catchment vegetation. Other studies in these same Mediterranean and monsoonal watersheds have examined temporal trends in stream chemistry using data specifically from storm events (Aguilera and Melack 2018b; Goodridge et al. 2018) or following a single fire (Dahm et al. 2015; Reale et al. 2015; Sherson et al. 2015; Sánchez et al. 2023), and several quantify fire and precipitation as an intertwined effect (Reale et al. 2015; Goodridge et al. 2018; Sánchez et al. 2023). Here, we examine these previous studies to illuminate patterns and mechanisms relevant to our findings, while providing novel insights into fire and precipitation interactions across distinct hydroclimates.

Surface and subsurface flowpaths connecting hillslopes and streams mediate the interaction of fire and precipitation

Surface and subsurface flowpaths between hillslopes and streams mediated responses to fire, producing distinct signals across hydroclimates. In a monsoonal hydroclimate (New Mexico), specific conductance responded most consistently to the interaction of burned area and precipitation, as storms mobilized materials that increased specific conductance in streams for prolonged post-fire periods. Our study builds upon previous observation of prolonged measures of increased specific conductance following monsoonal storms in one of the study streams (EFJ) for 7 months (Fig. 3 in Sherson et al. 2015) to 2 years (Fig. 3 in Reale et al. 2015) following fire. In this study, a similar pattern existed in two additional streams for 3 to 5 years post-fire (3 years of strong effects and 5 years of weak effects, Fig. 3 this study). Though use of monthly cumulative precipitation in the statistical models could not capture the effects of individual storms or shorter snowmelt periods, the data include years of higher and lower snowfall and seasonal variation in rain intensity and duration (both monsoonal and non-monsoonal) that are characteristic of this hydroclimate. We found that fire increased the availability of major ions for transport and that delivery to streams increased following precipitation (Fig. 3). The volcanic lithology and low-relief valleys cause deep groundwater to dominate streamflow generation in these watersheds (White et al. 2019), which likely

contributed to combustion-liberated ions being stored on the landscape or leached into deeper flowpaths for years until being transported to streams during periods of elevated hillslope flows (Sánchez et al. 2023).

In contrast to the monsoon-influenced streams, fire effects on major ions might be strongest in Mediterranean streams during periods of low hydrologic transport because dilution during storms obscures differences among burned and unburned catchments (Fig. 3). Consistent dilution of specific conductance following precipitation in all four streams indicated that rapid hydrologic runoff to streams, rather than fire or its interaction with precipitation, most strongly influenced transport of major ions to Mediterranean streams (Fig. 3). In the Santa Ynez Mountains where the Mediterranean watersheds are located, steep catchment slopes (10–100%, Hanan et al. 2016) and poorly developed soils result in significant runoff via shallow flowpaths following storms such that the mineral-rich groundwater that contributes major ions to baseflow is diluted (Rademacher et al. 2003).

Though fire had weak effects on major anions in Mediterranean streams, nutrient concentrations increased following fire and these effects were amplified by precipitation for inorganic nitrogen in many watersheds (Fig. 4), suggesting that runoff via shallow flowpaths transported nutrients to streams. Precipitation had a positive effect on both NO_3^- and PO_4^{3-} (Fig. 4), which aligns with past analyses that documented flushing of NO_3^- and PO_4^{3-} in the Mediterranean streams during storms (Aguilera and Melack 2018a, b). Runoff in these watersheds mobilizes large quantities of sediment (Warrick et al. 2015), and nutrients associated with sediment transport, particularly PO_4^{3-}, are elevated during periods of high discharge (Aguilera and Melack 2018b). These solute mobilization mechanisms may overwhelm signals of PO_4^{3-} accumulated following fire and removal of vegetation. However, positive interactive effects of fire and precipitation on inorganic nitrogen suggest that increased supply of nitrogen following fire or a change in flowpaths resulted in increased transport of nitrogen to streams in some watersheds (Fig. 4). Shallow flowpaths likely conveyed the nitrogen to streams, as previous analysis of the Rattlesnake Creek (RS02) focused at the scale of individual storms found elevated nitrogen concentrations during storms for 17 months after fire (Goodridge et al. 2018).

Responses to fire that are independent of precipitation might indicate how fire alters stream chemistry and watershed hydrology during baseflow conditions. Fire had a negative effect on specific conductance in one monsoonal stream two years following fire (RSAW), in contrast to the generally positive effects of fire and its interaction with precipitation on specific conductance (Fig. 3). We hypothesize that reduced transpiration following fire and greater water yield may have resulted in dilution and lower solute concentrations in streams at baseflow. In support of this hypothesis, the dilution effect of fire on specific conductance in the monsoonal climate occurred in the watershed with greatest forest cover, and combustion of accumulated forest biomass would likely reduce transpiration more than removal of grassland vegetation at the watershed scale. In addition, variation in the magnitude of fire effects on specific conductance observed among the monsoonal streams might have been influenced by the proximity of fire to streams. Ninety-four percent of the RED watershed burned, the greatest burn extent in the dataset (Fig. 1, Table 1), and this was the only monsoonal watershed with a weak but persistently positive effect of fire that was independent of precipitation (see immediate, 1, 2, 4, and 5 year durations in Fig. 3). The proximity of the burned area to the stream (0 m, Table 1) would have decreased the transport distance of combustion products to the stream, reducing hydrologic transport as a limitation on solute delivery and weakening the potential interaction with precipitation. In contrast, fires in the monsoonal RSAW watershed burned a relatively smaller area and occurred further from the stream (> 9 km, Table 1). As a result, more precipitation might have been required to mobilize burned materials from burned slopes to the stream, contributing to the observed positive effect of the interaction between percent of the watershed burned and precipitation on specific conductance there.

In Mediterranean streams, the effect of fire alone was primarily independent of precipitation but contrasted among watersheds and solutes. In one stream (GV01), a negative effect of fire on specific conductance strengthened over time (i.e., weak effects in 2–3 year durations followed by strong effects in 4–5 year durations, Fig. 3). In that same stream, we also detected positive effects of fire alone on NO_3^- (strong effect in 2–5 year durations, Fig. 4) and NH_4^+ (weak effect in 1–4 year durations, Fig. 4).

These effects of fire alone in the GV01 watershed were likely due to the proximity of fire to the sampling location (0 m, Table 1). We hypothesize that extensive burning of riparian vegetation in GV01 contributed to delayed recovery of watershed biogeochemical cycles and hydrologic flowpaths following the fire. Specifically, shallower flowpaths due to reduced transpiration in the absence of riparian vegetation would dilute specific conductivity compared to deep groundwater that typically supplies baseflow in these streams (Rademacher et al. 2003). In contrast, fire had a delayed (4 years post-fire), positive effect on specific conductance in two other streams (AB00, HO00, Fig. 3) where the fire was much further from the stream (> 6 km from AB00, Table 1) or the riparian vegetation cover was greater (HO00, 32%) than in GV01 (20%, Aguilera and Melack 2018b) which may have served to create a greater buffer between the fire and the stream. These opposing patterns suggest that fire in the uplands has contrasting effects on watershed biogeochemistry and hydrology compared to burning of the riparian zone.

Role of watershed vegetation in post-fire recovery

In addition to effects of hydrologic transport and fire characteristics, differences in vegetation across the study watersheds might have contributed to variation in the rates at which solute concentrations returned to pre-fire conditions. In Mediterranean watersheds, vegetation regrowth occurs rapidly after fire (Verkaik et al. 2013). In these streams, NH_4^+ concentration increased in sites located within the burn perimeter (Table 1), but only during the first six months following fire (Fig. 4). The watershed with the most persistent, positive interactive effect of fire and precipitation on both NH_4^+ and NO_3^- concentrations (RS02, Fig. 4) had the highest shrubland land cover (72%) as compared to other shrubland (AB00) or grassland-dominated (GV01) sites (Aguilera and Melack 2018b). Studies in the neighboring Santa Ynez Mountains found that post-fire nitrogen uptake was enhanced by rapid growth of herbaceous plants (Hanan et al. 2016), and herbaceous plants that grow immediately following fire may serve as a sink that limits nitrogen transport via runoff and retain nitrogen that was made available by incomplete combustion of biomass and post-fire microbial mineralization (Goodridge et al. 2018). We hypothesize that post-fire recovery of vegetation may have been slower in shrub-dominated watersheds, such as RS02, resulting in slower nitrogen uptake rates and greater transport of nitrogen to streams.

Riparian and wetland vegetation also likely influenced spatial and temporal patterns in stream chemistry after fire. Among the monsoonal streams, the positive interactive effect of fire and precipitation on specific conductance occurred over the shortest duration in EFJ (Fig. 3), a watershed with a higher proportion of valley bottom meadow habitat (approximately 38% of watershed area compared to 23% and 10% in RSAW and RED, respectively, Supplementary Table 2). Riparian cover could buffer streams from fire-induced changes in solute export particularly when the riparian zone remains unburned or recovers rapidly. In contrast, persistent, positive effects of fire on NH_4^+ and NO_3^- occurred in the Mediterranean watersheds with greatest riparian cover (Fig. 4; 20% in GV01 and 32% in HO00, Aguilera and Melack 2018b). A limited interactive influence of fire and precipitation on NH_4^+ and NO_3^- concentrations in these streams suggests that nitrogen sources (e.g., combustion byproducts or increased soil pools following removal of vegetation) were likely more proximal to the stream and less dependent on precipitation for mobilization.

Conclusion

Effects of fire on solute concentrations in aridland streams persisted from one to at least 5 years after fire and contrasted across hydroclimate regions and among catchments of varying slope, proximity of fire to the stream, and vegetation cover. Surface and subsurface flowpaths connecting hillslopes to streams appeared to mediate dilution versus flushing of specific conductance by precipitation. Persistent export of nitrogen occurred in watersheds whose dominant vegetation cover was slower-growing shrubs. Proximity of fire to streams intensified the effects of fire likely by reducing transport distance between accumulated materials and streams. A strong influence of precipitation on solute concentrations emphasized the extent to which intermittency in upland flowpaths contribute to the patterns of prolonged delivery of solutes from hillslopes to streams and the potential for delayed effects of fire in aridland streams. As both

fire frequency and precipitation regimes in the western U.S. change, it will become increasingly challenging for water quality managers to predict multi-scale, interacting effects of disturbances on aridland watersheds and streams. Changes in water quality may have far-reaching effects on ecological, agricultural, and municipal functions (Paul et al. 2022; Williams et al. 2022; Raoelison et al. 2023), particularly if they appear or persist on timescales longer than those for which data are available. The results of this study and others (Hampton et al. 2022; Murphy et al. 2023; Raoelison et al. 2023) highlight the critical need for additional water quality data collection over extended periods that encompass both pre- and post-fire conditions. Developing a quantitative understanding of the interactions between climate, hydrology, and fire at the terrestrial-aquatic boundary will improve our capacity to predict consequences for stream water quality and recovery of ecosystem function.

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Data availability The datasets analyzed in this study have been publicly archived by the Santa Barbara Coastal Long-Term Ecological Research program and the U.S. Geological Survey and are in the process of being publicly archived by the Valles Caldera National Preserve; please see references within the Methods and Supplementary Information for access information. The model fits generated by this study are publicly available on Zenodo at (https://doi.org/10.5281/zenodo.11199122).

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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