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Overview Article

Fire influence on land–water interactions in aridland catchments

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Abstract

Wildfires have increased in size, frequency, and intensity in arid regions of the western United States because of human activity, changing land use, and rising temperature. Fire can degrade water quality, reshape aquatic habitat, and increase the risk of high discharge and erosion. Drawing from patterns in montane dry forest, chaparral, and desert ecosystems, we developed a conceptual framework describing how interactions and feedbacks among material accumulation, combustion of fuels, and hydrologic transport influence the effects of fire on streams. Accumulation and flammability of fuels shift in opposition along gradients of aridity, influencing the materials available for transport. Hydrologic transport of combustion products and materials accumulated after fire can propagate the effects of fire to unburned stream–riparian corridors, and episodic precipitation characteristic of arid lands can cause lags, spatial heterogeneity, and feedbacks in response. Resolving uncertainty in fire effects on arid catchments will require monitoring across hydroclimatic gradients and episodic precipitation.

Keywords: accumulation, combustion, transport, propagation, streams

The spatial extent and intensity of wildland fire have increased globally over the past several decades because of historical fire suppression, land-cover change, climate warming, and increasing aridity (Holden et al. 2018, Senande-Rivera et al. 2022, Williams et al. 2022). These trends encompass arid lands (Dennison et al. 2014, Singleton et al. 2019, Salguero et al. 2020, Jones et al. 2022), defined by annual precipitation of less than 500 millimeters or an aridity index of less than 0.5 (precipitation divided by potential evapotranspiration; figure 1, Stringer et al. 2021). Arid lands account for approximately 45% of global lands (Prăvălie 2016, Koutroulis 2019) and are increasing in spatial extent and aridity as the climate warms (Huang et al. 2016, Singh et al. 2022). Disturbance by fire occurs within the context of variable precipitation regimes in arid lands (e.g., Mediterranean and monsoonal; Ballard et al. 2019, Konapala et al. 2020, Zhang et al. 2021, Senande-Rivera et al. 2022). Precipitation regimes are also changing, with increasing incidence and magnitude of floods and droughts that can diminish the delivery of ecosystem services and increase hazards (Archer and Predick 2008, Stringer et al. 2021). The interactions of changing fire and hydrologic regimes in arid lands portend substantial but variable consequences for ecosystems and the services they provide to human populations.

The dynamics of fire and its ecological effects in arid lands depend on hydrologic context. Fuel accumulation and moisture content, both correlated with local aridity, influence areal extent, frequency, and intensity of fire (i.e., energy released by combustion; Hanan et al. 2021, Juang et al. 2022, Ren et al. 2022). For example, invasive grasses establish and spread in response to years or seasons of high precipitation, and their accumulated biomass then promotes more frequent and larger fires (Balch et al. 2013). The initial decrease in evapotranspiration following combustion of vegetation, decreased albedo of burned soils and vegetation, and reduced shading under burned forests causes increased runoff and, in snowmelt-influenced catchments, earlier peak flows (Wine et al. 2018, Gleason et al. 2019, Biederman et al. 2022). Post-fire regrowth of vegetation depends in part upon precipitation regime and partitioning of water between runoff and storage (Parks et al. 2018, Buma et al. 2020) and the rate of regrowth in turn influences hydrologic connectivity and supply of water to receiving aquatic ecosystems.

Although temporary increases in streamflow following fires might benefit downstream municipalities and agriculture, burned catchments often deliver water of diminished quality. Postfire changes in water chemistry degrade drinking water quality,

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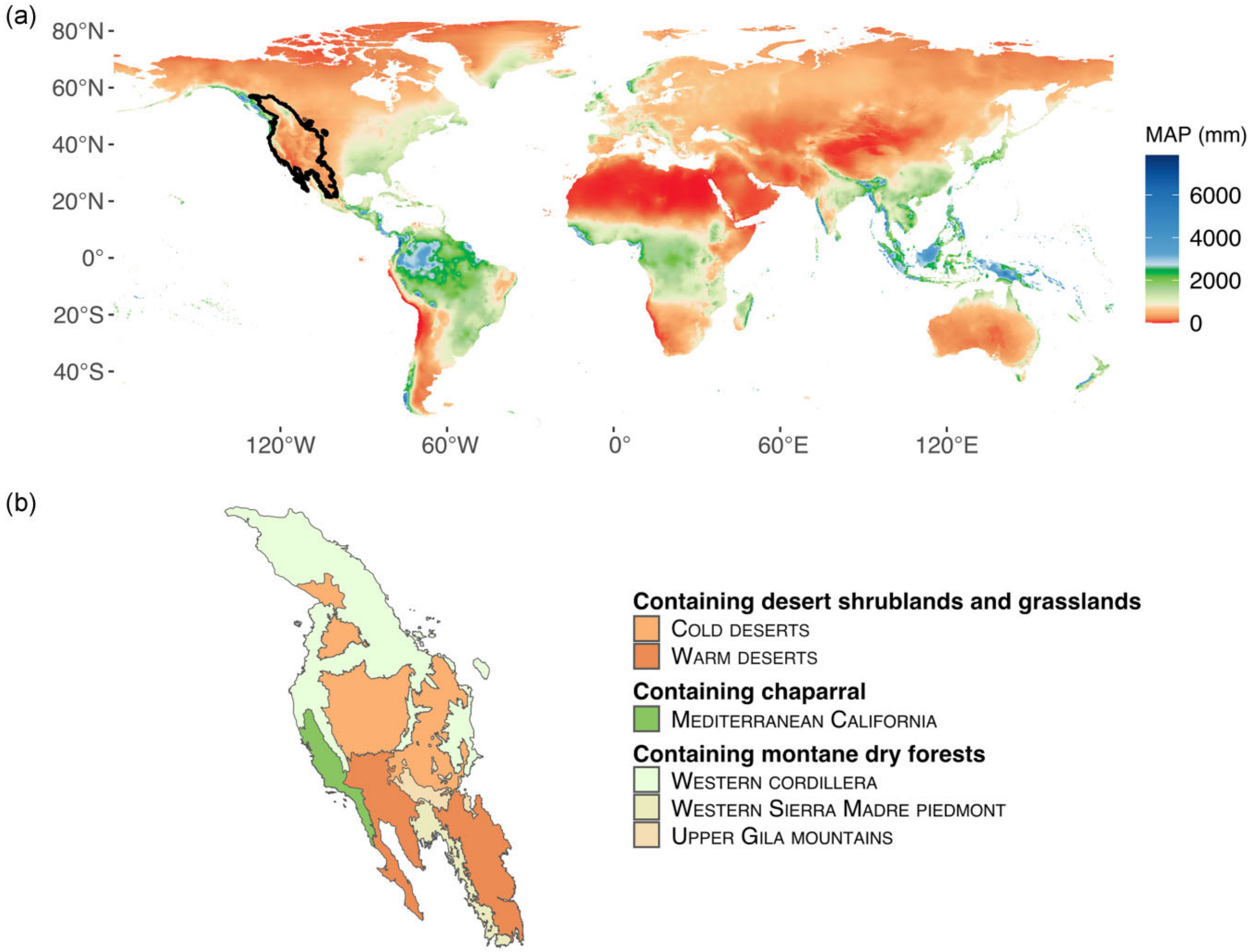

Figure 1. Arid lands (mean annual precipitation less than 500 millimeters) are extensive globally (orange shading in panel a). The examples in this article highlight three aridland ecosystems occurring within the western United States and Mexico outlined in black (b): desert, chaparral, and montane dry forests. Deserts encompass both cold and warm ecoregions, and grasslands occur within the south-central and west-central semiarid prairie ecoregions. Chaparral occurs within the Mediterranean California ecoregion. Montane dry forests occur within portions of the western cordillera, western Sierra Madre piedmont, and upper Gila Mountain ecoregions. Ecoregions from the US Environmental Protection Agency (Omernik and Griffith 2014; https://www.epa.gov/eco-research/ecoregions-north-america).

increase the cost of water treatment, and can increase the formation of disinfection byproducts (Murphy et al. 2015, Pennino et al. 2022). Erosion and debris flows following fires increase suspended-sediment loads and the delivery of substrata to stream channels (Dahm et al. 2015, Murphy et al. 2015, Warrick et al. 2015, Wilson et al. 2021, McGuire et al. 2024). Solutes concentrated in ash (Earl and Blinn 2003, Engle et al. 2008, Rust et al. 2019, Swindle et al. 2021, Johnston and Maher 2022) and reduced uptake of nutrients by burned terrestrial vegetation result in increased delivery of solutes to streams (Sherson et al. 2015, Goodridge et al. 2018, Aguilera and Melack 2018a, Rhoades et al. 2019, Gustine et al. 2021, Hampton et al. 2022). However, in aridland catchments, these effects of fire on aquatic ecosystems can be delayed because pulses of solutes and sediments are delivered from burned areas to streams primarily during rainy periods or snowmelt, and precipitation events that are large enough to mobilize solutes and sediments may lag fires by months to years (Murphy et al., 2012, Oliver et al. 2012, 2015, Sherson et al. 2015, Hanan et al. 2016, East et al. 2021). Hydrologic transport of solute and sediment pulses through river networks can also distribute the effects of fire beyond the burned perimeter to influence larger rivers that serve as important drinking water sources (Dahm et al. 2015, Emmerton et al. 2020, Ball et al. 2021).

Fire in aridland catchments

Arid lands encompass hyperarid, arid, and semiarid climates and are distributed globally (figure 1a). We summarize variation within the domain of arid lands by drawing from patterns observed across spatial and temporal gradients in hydroclimate, hydrologic connectivity, and fire susceptibility in the western United States. Specifically, we illustrate variation in responses of aridland catchments to fire by contrasting three aridland ecosystem archetypes: desert shrublands and grasslands, chaparral, and montane dry forests (figure 1b, box 1).

Water is the overarching factor driving the structure and function of aridland ecosystems (Noy-Meir 1973). The availability of water changes on spatial scales ranging from sites (e.g., variation in topography and aspect, under or between plants, drainage channels) to regions (e.g., elevation and latitudinal gradients in aridity, montane rain shadows). Heterogeneity in weather and

Box 1. Arid ecosystem archetypes.

Desert shrublands and grasslands encompass lower-elevation ecosystems along a gradient of seasonality in precipitation from winter-dominated rainfall in the Mojave Desert to summer-dominated rainfall in the Chihuahuan Desert. Mean annual precipitation ranges from less than 100 to approximately 350 millimeters, but interannual variability is high. Rapid overland flow in response to rainfall is common in desert shrublands and grasslands because of shallow, often hydrophobic soils. The five major deserts of North America (Great Basin, Mojave, Sonoran, Colorado Plateau, and Chihuahuan) occupy elevations below approximately 1000 meters in much of the intermountain West, extending from the eastern Sierra Nevada in California to New Mexico and south into the Mexican states of Sonora and Chihuahua. The deserts are characterized by assemblages of cacti and shrubs, the low densities of which historically impeded the spread of fire. Beginning with European colonization, nonnative, annual grasses that are susceptible to fire increased fire frequency in wet years (Schmid and Rogers 1988, Abatzoglou and Kolden 2011). Native grasslands, such as those in the Great Basin and Colorado Plateau, have more continuous cover that has historically permitted infrequent (approximately 60–80 years), low-intensity fire (McPherson 1995, USDA Forest Service). Experiments show that grassland community structure is resilient to global-change drivers of drying, warming, and nitrogen addition, but fire increases sensitivity to these drivers (Collins et al. 2017). Conversion of desert grasslands to shrubland is occurring throughout the southwestern United States, possibly as a consequence of fire suppression, with variable effects on aboveground carbon storage and therefore fire susceptibility (Van Auken 2000, Barger et al. 2011, D'Odorico et al. 2012).

Chaparral ecosystems occur at intermediate elevations (300–1200 meters) in a climate characterized by variable rainfall during cool winters followed by a warm, dry period, where terrestrial vegetation is dominated by evergreen shrubs (Keeley and Davis 2007, Parker et al. 2016). Long-term mean annual precipitation is approximately 200 to 600 millimeters and greater at higher elevation although rainfall varies significantly among years. In California, chaparral occurs in coastal mountains and the western side of the Sierra Nevada. Steep slopes in chaparral catchments, as in montane catchments, cause rapid routing of runoff to streams, even in the absence of overland flow. Chaparral plants tend to be adapted to high-intensity fires (i.e., those that reach the canopy) and regenerate after fire from dormant seed banks and resprouting from stems and lignotubers (Parker et al. 2016). Although the natural fire frequency is several decades (30 years or more), human activities and recent climate changes have increased the incidence of wildfires (Verkaik et al. 2013). Chaparral is a common ecosystem at the wildland-urban interface, because it surrounds major metropolitan areas (e.g., Los Angeles, San Diego) in California. Because of lower resilience to increased fire frequency and encroachment by annual grasses (Parker et al. 2016), there is high uncertainty regarding response of chaparral ecosystems to altered fire and precipitation regimes.

Closed-canopy forests occupy an estimated 2% of arid lands globally and play disproportional roles in aridland biodiversity and human livelihoods (Bastin et al. 2017). In the present article, we focus on *montane dry forests*, including pine and mixed conifer forests, that occur at higher elevations (greater than 1200 meters) throughout arid and semi-arid western North America. Montane dry forests in western North America are characterized by ponderosa, lodgepole, or Jeffrey pine, with mixed conifers including spruce and fir, and occur where snow constitutes a significant proportion of annual precipitation. Accumulated snow yields a seasonal pulse of meltwater to streams, often delivered via infiltration and interflow. Mean annual precipitation for this ecosystem is difficult to characterize because of uncertainties in forest distribution (Guirado et al. 2022), but the range limits of ponderosa pine provide an estimate of 250 to 1270 millimeters (Fryer 2018). Prior to European colonization, these forests experienced relatively frequent, low-intensity surface fires (i.e., those that do not reach the canopy) with a recurrence interval of approximately 30–60 years and infrequent, stand-replacing fires with a recurrence interval of approximately 150–500 years (Swetnam and Baisan 1996, USDA Forest Service). Fire has been suppressed for the past century or more and the resulting interaction of fuel build-up and increasing aridity has increased the risk of large and high-severity fires (Singleton et al. 2019, Juang et al. 2022) and forest-to-shrubland transitions (Guiterman et al. 2018). Prescribed burning and forest thinning are now being implemented to restore forest structure and fuel loads in some areas, with potential consequences for depletion or redistribution of major element stores in catchments (Engle et al. 2008).

climate patterns (e.g., Southern Oscillation) causes variation in water availability on temporal scales ranging from episodic storms to seasonal and interannual variation or multiyear dry and wet phases. Overall, spatial and temporal gradients in water availability establish patterns of fuel loading (figure 2), material stores susceptible to combustion, and the potential for post-fire transport of materials to stream networks. Potential fuels (i.e., plant biomass and detritus) accumulate slowly during dry periods and more rapidly during wet periods because of the limitation of ecosystem processes by water (Noy-Meir 1973, Collins et al. 2014). Widespread but episodic productivity, biogeochemical transformation, and transport of materials occur in uplands, which are dependent on the input of water from precipitation or snowmelt regimes characterized by high interannual variability and long intervening dry periods (Gherardi and Sala 2019, Ren et al. 2024). In contrast, more permanent but spatially discrete sources of water, such as that found in stream–riparian corridors, sustain material accumulation over longer durations (Harms and Grimm 2010, Collins et al. 2014). Characterizing the dynamics of fire and its ecological consequences in aridland catchments therefore requires an ecohydrological context that can account for significant spatial and temporal heterogeneity.

Fire regimes of arid lands, in turn, vary with aridity and productivity, which establish gradients of flammability and fuel loads, respectively (figure 2; Pausas and Paula 2012). In flammability-limited ecosystems, abundant fuel could support fire spreading, but high moisture limits its combustion (e.g., in high elevation forests or riparian zones; figure 2). As a result, flammability-limited ecosystems may incur large fires only during extreme drought (Steel et al. 2018), which is becoming more frequent with climate warming (Hanan et al. 2021). In more arid ecosystems, the flammability of potential fuels is greater, and fire is instead limited

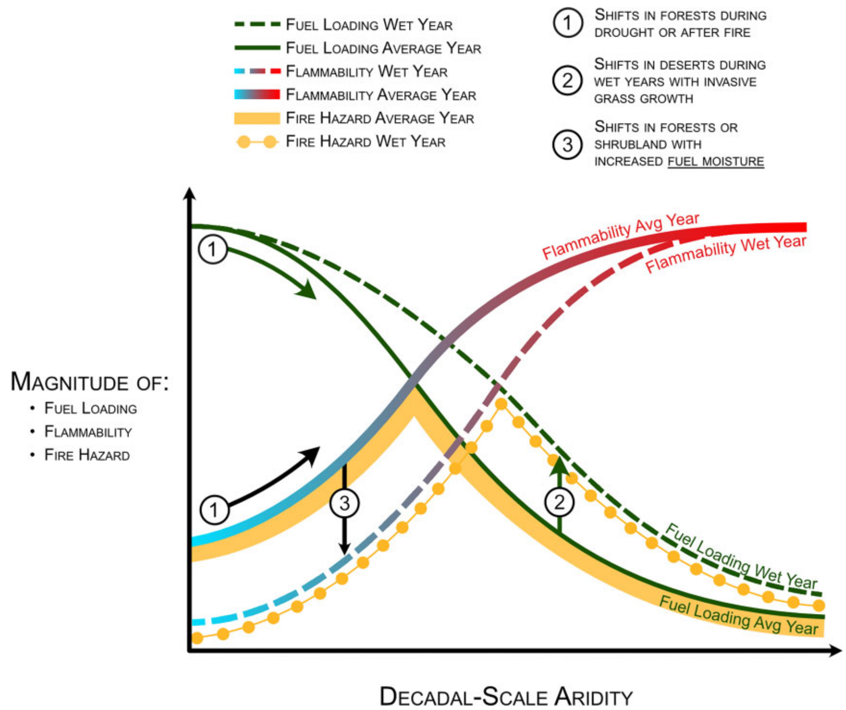

Figure 2. Aridland fire hazard varies along an aridity gradient (x-axis) in response to the relative effects of flammability and fuel loading. In aridlands, primary productivity (and therefore fuel loading) varies inversely with decadal-scale aridity and is also influenced by interannual precipitation patterns (wet versus dry years are particularly important in drier climates where productivity is generally low and annual grass cover can be high). Flammability increases with decadal-scale aridity and can be lower in wet years (particularly in more mesic systems where forest and shrub cover are higher) because of increases in fuel moisture. Fire hazard peaks where the two drivers intersect. Stochasticity in fire hazards results from nonlinear interactive effects of drought (1), species composition (2), and moisture (3). Source: The concepts in the present figure are extended from Pausas and Paula (2012).

by fuel accumulation (because of low productivity; figure 2). The degree of fuel limitation also varies along aridity and productivity gradients. In moderately arid locations (e.g., montane forests, such as southwestern ponderosa pine forests), frequent but low-severity fires are common and contribute to fuel limitation by consuming biomass. However, in some of these ecosystems, extensive twentieth-century fire suppression has increased fuel accumulation, leading to larger, more destructive fires. In strongly fuel-limited ecosystems (e.g., deserts), fire frequency and intensity are typically much lower (figure 2), but grass invasion in some of these landscapes has increased fuel continuity and therefore the incidence of fire during wet years (Brooks et al. 2004, Abatzoglou and Kolden 2011). Although aridland ecosystems are fuel limited on average, many of these landscapes occupy intermediate positions along the flammability to fuel-limitation continuum that may shift between these conditions because of daily, seasonal, and decadal spatial and temporal variation in moisture and productivity (e.g., a wet year in figure 2).

Conceptual model

We developed a conceptual model to examine how fire interacts with precipitation in arid lands to influence accumulation rates of matter, combustion, material transport, and associated feedbacks (figure 3). The conceptual model addresses ecological, hydrologic, and biogeochemical processes occurring at a catchment scale and over time scales from precipitation events to the recurrence interval of fire. The conceptual model emphasizes attributes and processes of particular importance to arid lands, such as episodic precipitation, that also apply to mesic regions undergoing droughts of increasing duration and severity (Grünzweig et al. 2022). The model builds on previous frameworks that emphasize how the spatial and temporal distribution of water influences biogeochemistry, hydrology, and primary productivity of arid lands (e.g., Noy-Meir 1973, Belnap et al. 2005, Collins et al. 2014). These pulsed dynamics of water availability, hydrologic transport, and material cycles have been conceptualized by trigger–transfer–pulse–reserve dynamics that describe a precipitation trigger of material transfer via hydrologic flowpaths and of pulsed biogeochemical activity, with unreacted materials retained in plant or soil reserves (Noy-Meir 1973, 2005, Sickman et al. 2003, Belnap et al. 2005, Collins et al. 2014). We extend this conceptual model to consider disturbance by fire and to explore the propagation of fire influence beyond the boundaries of burned ecosystems, with a focus on potential effects in streams and rivers. We then outline a research agenda to address uncertainties in the conceptual model, including hypotheses and priorities for data collection needed to predict responses of water quality to forecasted increase in fire, drought, and intense precipitation.

Accumulation

We define accumulation as the rate of matter accrual within a catchment. The accumulation rate is the balance of catchment inputs and outputs, which may be biological, meteorological, or hydrological. These inputs and outputs are, themselves, a function of several interacting processes, including photosynthesis, plant respiration, leaf turnover, litter breakdown by soil fauna, microbial decay and soil respiration, and export of particulate and dissolved materials. Other inputs to the ecosystem, such as nitrogen fixation and atmospheric deposition, also influence accumulation rates. For example, organic carbon accumulation can be

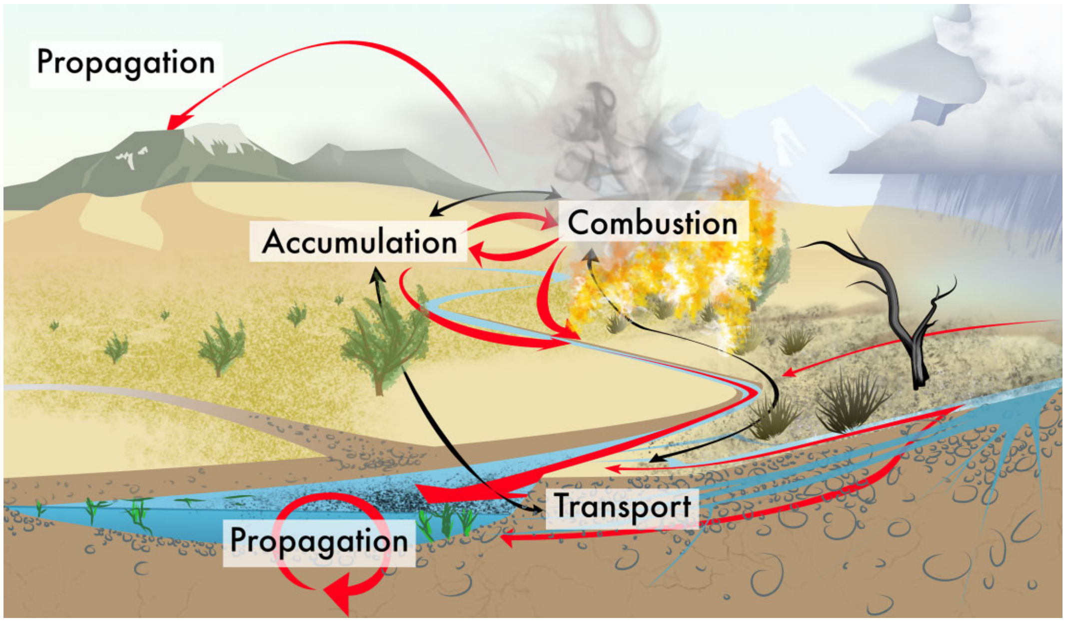

Figure 3. Accumulation, combustion, transport, and propagation processes (red arrows) and potential feedbacks among them (black arrows) predict the effects of fire in aridland catchments.

defined as the rate of gross primary productivity and imported carbon (e.g., hydrologic transport from upslope or atmospheric deposition) minus ecosystem respiration and hydrologic or aeolian export of organic carbon. In our conceptual framework, accumulation provides material for combustion and also influences the rate at which elements cycle and are immobilized over the course of recovery from fire (e.g., accumulating plant biomass will increase nitrogen immobilization). Therefore, to understand solute export over time following a fire, it is important to focus on rates of accumulation and how material cycles interact, rather than on standing stocks at a point in time.

Accumulation can be spatially heterogeneous in arid lands because of variation in soil moisture. For example, under the most arid conditions, water limitation results in patchy distribution of plants (Phillips and MacMahon 1981, McAuliffe 1988). Input of organic matter beneath the canopy of individual plants enhances nutrient recycling and increases water-holding capacity of soils, creating islands of fertility surrounding trees and shrubs that introduce canopy-scale heterogeneity in material accumulation (Schlesinger et al. 1995, Schlesinger and Pilmanis 1998, Klemmedson and Tiedemann 2000, Gundale et al. 2008, McCrackin et al. 2008). At larger scales, drainage networks organize patterns of primary production, whereby increased accumulation of plant biomass occurs along channels that drain larger contributing areas that support more permanent surface and shallow subsurface flows (Sponseller and Fisher 2006). At the scale of hillslopes, soil moisture and primary productivity of north-facing slopes exceed those of south-facing slopes where sparse vegetation enhances runoff (Gutiérrez-Jurado et al. 2013), although transpiration and infiltration into the rooting zone might buffer this effect in more productive montane forests (Pelletier et al. 2018).

Arid lands are characterized by acute temporal heterogeneity in water availability where high inter- and intra-annual rainfall variability can influence vegetation productivity, litter and fuel deposition, decomposition, and biogeochemical cycling on seasonal, annual, and decadal timescales (Hanan et al. 2022). Materials derived from litter, atmospheric deposition, and weathering accumulate in soils during dry periods and undergo rapid transformation on rewetting, resulting in oxidation, gaseous losses, sequestration in microbial biomass, or uptake by plants (Gallardo and Schlesinger 1995, Belnap et al. 2005, Hall et al. 2011, Yahdjian et al. 2011, Harms and Grimm 2012, Homyak et al. 2016, Ren et al. 2024). Whereas the supply of accumulated substrates and nutrients often limits the duration of pulsed microbial activity following rain (Sponseller and Fisher 2006, Collins et al. 2014), plants respond to precipitation at seasonal to decadal scales, potentially resulting in asynchrony of nutrient availability and plant uptake. For example, arid grasslands exhibit later green-up during years of low winter precipitation (Currier and Sala 2022), which may decrease cumulative rates of nutrient uptake across the growing season.

Plant species have adapted different strategies that enable them to survive or recolonize following fire that influence spatial and temporal patterns of biomass accumulation. For example, in chaparral ecosystems, there is sufficient moisture to support relatively rapid shrub growth, which forms closed canopies of contiguous, relatively dry fuels (Rundel 2018). In these ecosystems, species recover or recruit quickly following severe crown fires because of traits such as fire-stimulated recruitment, obligate seeding, and resprouting from belowground lignotubers (Keeley and Pausas 2022). In dry forests, there is also sufficient moisture for fuels to accumulate, but frequent surface fires may maintain discontinuity between the forest floor and canopy. In these environments, long periods between fires under fire suppression result in greater accumulation of dead surface fuels and ladder fuels (i.e., fuels that connect surface fires to the canopy), leading to greater combustion by larger, more severe fires. In deserts, the most arid and fuel-limited ecosystems, species such as creosote bush, bursage, and saguaro are not adapted to fire and historically have been subject to infrequent fire because they grow at low density separated by biocrusts or bare soil (Condon et al. 2023) and reaccumulate biomass slowly after burning (Brown and Collins 2023).

Accumulated materials have three possible fates: combustion, transport, or storage. Combustion oxidizes accumulated material and releases it to the atmosphere in gaseous forms (Certini 2005) or as fine particles with smoke (Sokolik et al. 2019). Residual material is then deposited on the soil surface as ash and char (Bodí et al. 2014) and is subject to transport or reaccumulation via immobilization by recovering plants and soil microbes and adsorption to soil particles (Kutiel and Naveh 1987). These fates (both before and after combustion) are influenced by the amount of material that has accumulated and how materials are transformed by biogeochemical processes, both of which respond to precipitation. For example, in the three aridland ecosystem archetypes considered in the present article, both the amount and timing of precipitation influence plant productivity and nutrient uptake (Samuels-Crow et al. 2020, Liu et al. 2021, Alexander et al. 2023).

Spatial and temporal heterogeneity in soil moisture and accumulation processes can interact in complex ways to influence the fates of accumulated materials within catchments. For example, ash deposition after fire can contribute a pulse of readily decomposable organic nitrogen, which may accumulate under dry conditions or may be mineralized in wetter soil microsites (Parker and Schimel 2011). During subsequent storms, the accumulated nitrogen can be flushed before plants can take it up, even in nitrogen-limited ecosystems (Homyak et al. 2016, Hanan et al. 2017, Ren et al. 2024). Spatial and temporal variation in fuel accumulation also drives patterns of fire hazard and severity, particularly in fuel-limited arid lands (Coop et al. 2020). For example, accumulated litter provides a horizontal matrix for surface fires to spread, whereas understory vegetation (i.e., ladder fuels) can promote vertical fire spread or torching (Agee and Skinner 2005). Because fuel accumulation influences combustion temperatures, extent, and residence times (Kreye et al. 2013), it indirectly influences the cycling and transport of other accumulated materials (e.g., nitrogen and phosphorus), which may feed back to influence patterns of material accumulation (table 1).

Combustion

Combustion rapidly transforms soil organic matter, litter, and aboveground biomass into chemical energy, volatilized compounds, minerals, and ash (Bodí et al. 2014). Chemical, moisture, and mineral content of fuels interact with the spatial distribution and vertical structure of fuels to limit combustion efficiency in wildfires (Ottmar 2014, Urbanski 2014). Incomplete combustion produces methane, nitrous oxide, carbon monoxide, volatile organic carbon compounds, nitrogen oxides, and fine and coarse particulate matter. Incomplete combustion products remaining in ecosystems include char (or pyrogenic organic matter) and ash (a byproduct that consists of minerals and wildfire-produced char), both of which vary in composition according to completeness of combustion (Bodí et al. 2014). Both ash and char can be subsequently mobilized to streams (Earl and Blinn 2003, Chow et al. 2019, Chen et al. 2020). These byproducts of combustion may differ in morphology, light absorption, chemical stability, and composition (Zimmerman and Mitra 2017) and, therefore, have wide-ranging physical, biological, and chemical effects on stream ecosystems (Earl and Blinn 2003, Dahm et al. 2015).

The composition of byproducts of combustion depends on the interaction of fuel and fire characteristics. Along the combustion continuum, higher temperatures produce smaller char that is less reactive with relative increases in nitrogen and aromatic content and decreases in hydrogen to carbon and oxygen to carbon ratios (Masiello 2004, Wagner et al. 2018, Wozniak et al. 2020, Bahureksa et al. 2022). Ash can be characterized as white ash, which is produced by high-efficiency combustion and contains little organic matter, or as black ash, which forms under lower combustion efficiency (e.g., during smoldering combustion) and contains more residual and pyrogenic materials (Bodí et al. 2014). Lighter elements are typically volatilized at lower combustion temperature (i.e., nitrogen at a lower temperature than potassium, followed by phosphorus, sodium, magnesium, and calcium; Certini 2005, Bodí et al. 2014) such that fire intensity determines the composition of combustion products. Fuels also influence fire characteristics, including the amount of energy or heat produced (i.e., fire intensity), the time that fuel particles spend in flaming combustion (i.e., their residence time), and the rate of fire spread (Neary et al. 1999). Although data describing fire intensity, residence time, and rates of spread are valuable for predicting chemical transformations during and after fire, these data are not often available. Therefore, fire size and fire severity (or the extent to which an ecosystem is transformed by fire) provide useful indirect metrics of fire characteristics and can be acquired with remote sensing. For example, indices such as the difference-normalized burn severity index can provide estimates of aboveground burn severity. However, this index and related remote-sensing approaches overestimate high-severity fire in arid grasslands and shrublands because of short-statured vegetation that is often entirely consumed by fire (Roy et al. 2006, Gale and Cary 2022).

Climate, vegetation, and land cover in arid lands determine how combustion changes soil, litter, and aboveground biomass. In deserts, biomass and detritus are discontinuous (Abatzoglou and Kolden 2011), which results in patchier spread of fire and combustion efficiency. Chaparral vegetation in Mediterranean climates tends to be more homogeneously susceptible to combustion because of the high concentration of oils in their plant tissues (Almendros and González-Vila 2014), seasonal drought, and a continuous canopy (Parker et al. 2016). Fire severity in montane dry forests varies because of differences in density and moisture content of vegetation (Baker and Williams 2018). In addition, spatial and temporal patterns in precipitation cause variation in fuel moisture, affecting the occurrence and efficiency of combustion (Jeronimo et al. 2019). Over longer time periods, interannual variability of precipitation can affect forest structure, increasing the heterogeneity of fuels (Pfister and Bugmann 2000). However, vegetation responses to future climate forcings will likely be nonstationary as precipitation becomes more variable (Zhang et al. 2021).

Transport

The products of combustion are transported by wind and water, resulting in vertical and horizontal redistribution within catchments or movement to a different domain (figure 2). In the present article, we focus on hydrologic transport, the dominant pathway delivering combustion products to streams. Snowmelt runoff and groundwater recharged from mountains typically supply baseflow to aridland streams (Markovich et al. 2019, Tang et al. 2019). In arid montane catchments, interannual variation in snowpack strongly influences variation in baseflow and annual solute fluxes (Perdrial et al. 2014, Rumsey et al. 2020). Across all arid lands, infrequent, high-intensity storms rapidly route water over land or via shallow soils and networks of intermittent channels, delivering large pulses of materials to streams (Belnap et al. 2005, Brooks et al. 2007). Hydrologic connectivity of aridland catchments therefore varies as a function of the timing, intensity, and amount of precipitation, and the interstorm accumulation of materials results in large fluxes to streams following reestablishment of hydrologic connectivity (Welter et al. 2005, Brooks and Lemon

Table 1. Potential fire-initiated feedback loops influencing accumulation, combustion, transport, and propagation.

Initiating event	Feedback	Examples
Combustion of belowground biomass reduces soil stability	Decreased soil stability slows recovery of vegetation, leading to more soil erosion	One of the most commonly observed post-fire feedbacks particularly on steeper slopes (for a review, see Shakesby and Doerr 2006), but elevated erosion rates can be successfully mitigated (Girona-García et al. 2021) allowing for the re-establishment of vegetation.
Combustion of aboveground biomass decreases shading by the vegetation canopy and increases evaporation	Lack of canopy increases solar radiation resulting in earlier snowmelt, which dries soils and slows regrowth of vegetation	Following a fire in the Oregon Cascades, more snow accumulated in a burned forest, but the snowpack disappeared 23 days earlier and had twice the ablation rate than in an unburned forest, resulting in drier soils (Gleason et al. 2019).
Combustion of aboveground biomass results in reduced nutrient uptake by plants	Decreased vegetation increases lateral export of nutrients, reducing soil nutrient pools, and decreasing vegetation growth	Soil carbon and nitrogen declined by more than 35% after 64 years of frequent burning compared with unburned plots (Pellegrini et al. 2018). Exposed soils were vulnerable to leaching at the onset of autumn rains in chaparral ecosystems before recovering plants and microbes could access available nitrogen (Hanan et al. 2016).
Combustion of aboveground biomass reduces the population of fire-avoidant plant species, allowing fire-adapted species to establish	Dominance by fire-adapted vegetation increases susceptibility to combustion and thereby competitive advantage for fire-adapted species	In the Great Basin, Landsat images revealed that burned areas had higher annual herbaceous cover (e.g., cheatgrass) relative to sagebrush cover than unburned areas, suggesting that once annual grasses establish they increase the likelihood of fire (Barker et al. 2019). Alternatively, Tepley and colleagues (2018) suggested that flammable, early-successional vegetation regrowth amplifies risk of future fires, whereas less flammable early colonizers can reduce future fire risk.
Fire-damaged biomass transported to stream-riparian corridor	Accumulation of organic debris in riparian zones following fires and subsequent floods increases fuel load and fire hazard	Pettit and Naiman (2007) suggested a lagged feedback between fire, flood frequency, and forestry practices that determines the accumulation of woody debris and litter in riparian corridors that could serve as fuel for subsequent fires.
Fire-damaged biomass transported to upland swales or stream-riparian corridor	Accumulation of organic debris can sequester nutrients and retain water, increasing microbial retention of nutrients and reducing export	Transported sediments accumulated behind erosion-control structures in burned watersheds and collected sediments enhance microbial activity (Callegary et al. 2021).
Postfire contamination of drinking water by combustion byproducts increases expenses for cleaning water and can reduce access to clean drinking water	Diminished access to drinking water or expense of treating contaminated water quality leads to change in fire management within the contributing watershed	Feedbacks between fire management and downstream water quality have been incorporated into the Rio Grande Water Fund governance structure (Morgan et al. 2023).
Regrowth of herbaceous vegetation (accumulation) after a fire	Herbaceous vegetation promotes nutrient turnover that supports subsequent shrub growth and fuel loads	Goodridge and colleagues (2018) hypothesized that herbaceous plants are more easily decomposed, promoting soil microbial growth and organic nitrogen uptake, and subsequent nitrogen mineralization and nitrification that enhance shrub regrowth.

2007, Harms and Grimm 2010, Aguilera and Melack 2018b). Whether flows occur primarily over land or via the subsurface influences the types of materials transported, opportunities for retention and transformation during transit, and the timing of material delivery (Meixner et al. 2007, Liu et al. 2008, Welter and Fisher 2016).

Fire can change the routes and timing of hydrologic transport through catchments. Reduced transpiration following combustion of vegetation increases subsurface storage of water and streamflow (Kinoshita and Hogue 2015, Bart and Tague 2017, Collar et al. 2022, Hampton and Basu 2022, Atwood et al. 2023, Rey et al. 2023). The increased hydrophobicity of heated soils, decreased infiltration capacity caused by ash-clogged soil pores, and reduced vegetative cover contribute to rapid overland flows, shallow runoff, and reworking of channel networks by erosion and sediment deposition during storms (DeBano 2000, Woods and Balfour 2010, Bodí et al. 2014, Ebel et al. 2022, McGuire et al. 2024). Fire also affects the quantity and timing of snowmelt because of changes in forest structure and energy budgets that affect snow interception, redistribution, and melt dynamics (Moeser et al. 2020). For example, because ash deposition reduces albedo, fire causes earlier snowmelt in montane dry forests (Gleason et al. 2019, Smoot and Gleason 2021, McGrath et al. 2023), but reduced canopy cover can either increase or decrease snowpack (Goeking and Tarboton

2020). Net effects of fire on snowmelt have been thus far difficult to generalize, particularly for arid lands where solar radiation can be high (Goeking and Tarboton 2020, Moeser et al. 2020).

Whether generated by snowmelt or rain, rapid runoff via shallow flow paths transports combustion products and nutrients that accumulate after a fire. For example, in the chaparral regions of central California, peak discharge and suspended sediment export were 10 times greater in burned watersheds, and nitrogen export was 30 times greater than in neighboring, unburned catchments (Coombs and Melack 2013, Aguilera and Melack 2018a). Similar increases in solute fluxes were observed after fires in arid montane catchments (Sherson et al. 2015, Sánchez et al. 2023). Changes to catchment hydrology, including increased shallow or overland flows during storms in part explain elevated solute concentrations, particularly of inorganic ions, that persist for several years after fire (e.g., Jung et al. 2009, Murphy et al. 2018). Hydrologic changes can persist for decades following fire (Niemeyer et al. 2020, Williams et al. 2022) with variation in duration of effects attributed to the extent and severity of fire (Hallema et al. 2018, Wagenbrenner et al. 2021) and the rate of vegetation regrowth (Tague et al. 2019).

Episodic precipitation in arid regions results in pulsed delivery of combustion products and accumulated materials to streams, which may lag fires because of variability inherent in the precipitation regime. Large loads of materials delivered during the first precipitation or snowmelt event after fire can exhaust material stores accumulated after fire, limiting the duration of fire effects on streams. For example, nitrogen export from one chaparral watershed was 15 times higher than its prefire export during the first rain following fire and returned to prefire levels within about 3 months of postfire rainstorms (approximately 11 months after fire; Goodridge et al. 2018). Reduced hydrologic connectivity between catchments and streams during dry periods allows opportunities for transformation and loss of combustion products (e.g., photooxidation, biotic uptake) before they can be transported to streams. In contrast, incomplete flushing of combustion products because of reduced hydrologic connectivity during drought can delay or prolong the effects of fire on stream chemistry. For example, ions and sediment were repeatedly flushed from burned catchments during storms for several years following a fire in montane forests, whereas concentrations were similar between burned and unburned catchments during baseflow (Murphy et al. 2015). Combustion products might also be transported to the vadose zone or channel corridors, where they can continue to supply elevated loads to streams for several years after fire (Chorover et al. 1994, Sánchez et al. 2023, McGuire et al. 2024).

Interannual variability in precipitation has increased in arid lands over the past five decades (Zhang et al. 2021) and will likely continue to increase under climate change (Donat et al. 2016). In temperate climates, increased air temperature and evapotranspiration may offset increased precipitation, leading to negligible impacts on annual stream discharge (Campbell et al. 2011). In contrast, the increasingly variable precipitation expected in arid regions is likely to enhance temporal variation in stream discharge (e.g., lower flows in drier years, no change in wetter years; Hansford et al. 2020), potentially amplifying the pulsed nature of material transport to streams. Reducing uncertainty in the effects of fire on aridland hydrology and material transport will therefore require characterizing transport processes within the context of changing precipitation regimes.

Propagation

The effects of disturbances can propagate beyond the boundary of the disturbance (figure 2). Propagation of fire effects defines post-fire changes to accumulation, transport, or combustion processes in an unburned ecosystem caused by material flows or energy flux received from a burned area. Propagation is strengthened by proximity or connectivity between burned and unburned ecosystems, as well as by larger or more severe fires. Resilience of the receiving ecosystems to fire-initiated changes limits propagation. The interplay of fire attributes, proximity or connectivity with the burned ecosystem, and resilience of the unburned ecosystem therefore establishes gradients in the type and intensity of post-fire changes to unburned ecosystems in space and time. In the present article, we focus on the propagation of fire effects from uplands to streams, although we recognize that propagation also occurs in unburned uplands and marine ecosystems; for example, fertilization by ash deposition in coastal zones can stimulate phytoplankton growth (Tang et al. 2021).

Fire effects propagate to stream–riparian corridors with the delivery of water and materials from burned uplands. For example, following immediate post-fire removal of macrophyte biomass by high flows and elevated turbidity in an arid, montane stream, input of nutrient-rich sediment stimulated rapid regrowth of macrophytes, with different species-specific patterns of biomass accumulation compared with pre-fire conditions (Thompson et al. 2019). The stimulation of primary production and respiration in concert with the reduced use of detritus by higher trophic levels following the experimental addition of burned organic matter to mesocosms provides a similar example of propagation by changing patterns in accumulation of aquatic biomass (Wall et al. 2024). Longer-term changes to nutrient accumulation and transport result when fire changes the streambed substrata. Sediment or ash rich in phosphorus can sorb to the streambed, diminishing the capacity to abiotically retain additional phosphorus inputs, with the desorption of phosphorus prolonging the duration and distance over which elevated phosphorus concentration occurs in stream water (Son et al. 2015, Emelko et al. 2016). Ash deposition can also propagate effects over the long distances that fine particles can be transported (Earl and Blinn 2003). Deposition of fine particles might then influence within-channel patterns of transport by limiting hyporheic exchange, with concomitant influence on biogeochemical transformations and associated rates of accumulation. The potential for propagative effects of fire on streams because of changes in channel or network morphology caused by erosion, debris flows, or combustion of riparian vegetation remain little explored.

The propagation of fire effects to aridland streams often lags combustion because of infrequent precipitation and intermittent or episodic hydrologic connectivity between burned uplands and streams. For example, the concentrations of inorganic nitrogen in chaparral streams were increased during wet periods for several years following fire, and this effect was greatest in a catchment dominated by slow-growing shrubland vegetation (Lowman et al. 2024). Therefore, these nutrient inputs might propagate the effects of fire by stimulating nutrient-limited processes in streams for years after the fire. Propagation effects may also be distributed longitudinally throughout the channel networks in arid lands because the limited infiltration capacity characteristic of some aridland or burned soils combined with large or intense storms can result in flash floods that transport materials over large distances. For example, pulses of hypoxia in desert rivers observed up to 40 kilometers downstream from inputs of burned tributary catchments were likely caused by export of carbon and nutrients that fueled microbial metabolism in rivers (Dahm et al. 2015).

Feedbacks

Feedbacks, where the dynamics or output of a system influence the future state of the system, can generate nonlinear relationships among accumulation, combustion, and transport processes (table 1). The synergistic (i.e., positive or amplifying feedback loops) or antagonistic effects (i.e., negative or stabilizing feedback loops) of these interactions further affect the patterns of downstream propagation and catchment recovery from fire (table 1). Importantly, feedbacks can occur at multiple spatial and temporal scales and are strongly influenced by environmental context. In arid regions, the likelihood and strength of feedbacks are particularly sensitive to climate context, such as the timing and amount of rainfall or snowmelt.

The context within which a feedback occurs influences the direction and magnitude of the feedback. For example, in wetter ecosystems that support sufficient fuel accumulation, there is a strong negative relationship between fire frequency and severity (Steel et al. 2015), wherein longer periods between fires are more likely to result in greater accumulation and, therefore, greater combustion by larger, more severe fires. The amount of prefire accumulation in the uplands affects the availability of combustion products for transport after fire (Fuentes-Ramirez et al. 2015) and the loads and routes of transport, because vegetation and soil organic matter modify sediment movement and surface runoff (Sánchez et al. 2023). In addition, greater fuel loads can increase fire severity and vegetation mortality (Fitzgerald 2005, Stephens et al. 2018), thereby slowing the accumulation of biomass in the years following a fire, forming a stabilizing feedback between accumulation and combustion. Severe fire also deposits available and readily mineralizable nutrients as ash (Hanan et al. 2016, Pellegrini et al. 2018), and when postfire regrowth is slow, these nutrients become more vulnerable to export (Hanan et al. 2017). The likelihood, type, and intensity of feedbacks, however, depend on a wide range of biogeographic factors, including the biotic community, slope, and soil characteristics. For instance, fire-adapted grasses such as invasive buffelgrass grow quickly, provide abundant fuel for fire, and increase erosion and runoff (Marshall et al. 2012). This combination of traits contributes to an amplifying feedback, wherein fire promotes recruitment of invasive grasses, which, in turn, intensifies subsequent fires, increasing runoff and accelerating the loss of materials from soils (D'Antonio and Vitousek 1992, Horn and St. Clair 2017). In contrast, the establishment of less flammable species during early succession may reduce the likelihood of fire (table 1). Although inherently stochastic, identifying which biogeographic factors influence the intensity and direction of feedbacks will reduce the uncertainty in predicting post-fire catchment responses.

The direction and magnitude of feedback loops are scale dependent, and the nature of cross-scale interactions can determine the ultimate fate of materials (Heffernan et al. 2014). Lags between combustion and transport of combustion byproducts or materials accumulated after fire are caused by a pulsed precipitation regime (e.g., Verkaik et al. 2013, Hanan et al. 2017, Aguilera and Melack 2018a, Goodridge et al. 2018). As a result, the processes contributing to feedbacks might be occurring at distinct temporal scales, with initiating and reciprocal events separated in time. For example, fires that occur early during the dry season result in little export of materials to streams relative to fires occurring late in the dry season (Townsend and Douglas 2000), perhaps because regrowing vegetation can retain materials made available by combustion in the absence of drought stress earlier in the dry season (table 1; Hanan et al. 2017). Similarly, the small-scale distribution of water within catchments can influence the larger-scale fire regime. For example, within montane forests, moist meadows can intercept and retain materials exported from much larger burned areas (Oliver et al. 2012), which promotes persistence of fire-resistant meadows and potentially contributes to a negative cross-scale feedback that impedes spread of future fires (Stephens et al. 2021).

Although many feedbacks are initiated within the biophysical system, strong feedbacks associated with fire can arise in the broader social–ecological system. For instance, degraded water quality can prompt management actions that feed back on fire activity (table 1). Sediment, organic matter, and other materials mobilized after fires can degrade water quality (Paul et al. 2022), and material pulses may be transported to large rivers distant from the burn (Ball et al. 2021). Degraded water quality due to fire has necessitated the shutdown of water treatment plants and the use of alternative water sources (Dahm et al. 2015). Basin-scale changes in fire management strategy motivated by degraded water quality could provide a stabilizing feedback between wildfire risk and material loading to river networks. For example, the Upper Rio Grande watershed provides drinking water to approximately half of New Mexico's population and vulnerability of the basin to fire has prompted the Rio Grande Water Fund to coordinate fuel removal and prescribed burns to reduce the intensity of subsequent fires (Morgan et al. 2023).

Synthesis: Reducing uncertainty in responses of aridland catchments to fire

Fire has clear but variable effects on catchment hydrology and biogeochemistry, with up to tenfold variation across catchments and fires in the duration of responses and downstream distances over which the effects appear in streams (Rust et al. 2018, Hampton et al. 2022, Paul et al. 2022). The mechanisms underpinning these variable responses remain uncertain, and it is therefore difficult to predict how fire will affect catchments, particularly in arid lands, where variation in precipitation contributes to uncertainty in hydrologic and ecological processes at multiple temporal scales. To stimulate research, we pose a set of hypotheses that might explain responses of catchment hydrology and biogeochemistry to fire in arid lands (table 2). These hypotheses emphasize how fire interacts with accumulation, combustion, transport, and propagation processes to affect the type, distance, duration, and magnitude of stream responses, although we note that attributes of catchments, including slope, hydrologic connectivity, channel complexity, infrastructure, and the capacity for material retention also influence hydrologic and biogeochemical responses in streams. We outline a research agenda organized around tests of these hypotheses to both resolve uncertainty in fire effects on streams and leverage observations in streams to improve understanding of accumulation, combustion, and transport processes in connected terrestrial and stream ecosystems of aridland catchments.

The types of responses to fire vary among catchments that contrast in physical, climatic, or biotic attributes, as well as among fires in similar catchments. For example, studies that include post-fire monitoring of multiple constituents in streams have

Table 2. Research agenda for examining connectivity between burned catchments and fluvial networks with potential hypotheses.

Observations	Research Questions	Hypotheses
Dominant stream response to fire varies across fires and catchments and might include particulate loads, dissolved organic matter concentration, concentrations of inorganic ions, and/or dissolved oxygen sags	Why do the types of stream biogeochemical responses to fire vary among aridland catchments?	Elemental composition of postfire exports is influenced by the interaction of the stoichiometry of accumulated materials with fire intensity, because volatilization of elements varies with temperature (i.e., carbon is less volatile than nitrogen, which is less so than potassium, phosphorus, sodium, magnesium, and calcium). Attributes of accumulated fuel that influence combustion efficiency (e.g., moisture content, packing ratio, chemistry) influence post-fire availability of particulate relative to dissolved materials and distribution of particle sizes.
Variation in transport distances of combustion products and fire-liberated solutes: Fine ash is transported farther than coarse ash (Earl and Blinn 2003); sags in dissolved oxygen measured more than 50 kilometers downstream of a burn scar (Dahm et al. 2015); elevated phosphorus concentration more than 10 kilometers from the burn (Son et al. 2015)	What causes variation in the downstream distances over which signals of fire are detected in aridland stream networks?	Longitudinal extent of fire signals depends on the mobility of materials derived from combustion or within the fire scar. Mobility, via upland flowpaths and within streams, is, in turn, related to size and molecular composition of materials, which vary as a result of fire intensity. Larger loads of materials, derived from steeper slopes, greater accumulation of vegetation, larger fires or fires located nearer to channel networks, persist over longer distances within channels. Burial of biota or clogging of hyporheic exchange by ash or eroded sediment alters the physical structure of flowpaths and reduces material retention in stream channels, thereby increasing transport distance.
Duration (weeks to years) and magnitude (up to thirtyfold) of post-fire changes in stream chemistry, ecology, and hydrology vary among response types (e.g., by solute) and across events and catchments (Paul et al. 2022)	Why do the duration and magnitude of fire effects on stream ecosystems vary among response types and catchments?	The duration and magnitude of fire-driven material pulses depend on the amount and chemical composition of combustion products, which are a function of pre-fire material stores, burn size, and burn intensity. The duration and magnitude of fire-driven material pulses depend on the time between fire and precipitation: Longer gaps between fire and precipitation will increase duration of stream biogeochemical signals, including time until a signal is observed, because precipitation drives transport of materials from burn scars to streams. Longer gaps between fire and precipitation will decrease the magnitude of stream biogeochemical signals because biotic and abiotic transformations of combustion products in uplands decrease stores. The duration and magnitude of fire-driven material pulses depend on resilience to fire in the burned catchment. Ecosystems less adapted to fire will transmit larger signals of fire to streams over a longer time period because of weak internal feedbacks, which would otherwise more rapidly return the ecosystem to a pre-fire state.

documented pulses of inorganic nutrients as the dominant response to fire in some streams or following some fires, whereas pulses of dissolved organic matter have been a predominant response in others (Coombs and Melack 2013, Rust et al. 2018, Santos et al. 2019, Hampton et al. 2022). Likewise, some fires result in increased particulate loads, whereas others do not (Mast and Clow 2008, Moody and Martin 2009). The expected changes in water quality for particular regions, catchment attributes, or fire intensities could contribute to preparedness and mitigation of fire effects. Although we recognize that the timing of post-fire observations influences which responses are documented, we hypothesize that the types of chemical responses (e.g., organic versus inorganic; particulate versus dissolved) to fire vary because of the efficiency of combustion, which results from interactions of fire intensity with the attributes of accumulated materials (table 2) and determines the form and abundance of materials available for transport to streams after fire. Variation in the susceptibility of these materials to hydrologic transport could further influence the delivery of materials to streams following fire (table 2).

Projecting the distances over which fire affects water quality and riverine processes would support planning by communities dependent on water resources derived from catchments vulnerable to fire. In river networks, transport distances depend on the relative rates of material inputs and instream reaction or retention rates (Wollheim et al. 2021). We hypothesize that the factors influencing the mass of combustion products delivered to streams relative to discharge, including accumulated fuels and the proximity of burned areas to streams, determine transport distances in stream networks (table 2). Alternatively, the composition of materials loaded to streams from burned areas might influence rates of biogeochemical reactions or physical processes that retain or remove materials. Finally, we hypothesize that the loading of particulate materials from burned areas could reduce hyporheic exchange, limiting the opportunity for biogeochemical reactions that contribute to material retention and removal in streams (Krause et al. 2011).

The documented effects of fires on stream chemistry and biota range several orders of magnitude and persist for durations of less than a year to multiple decades (Paul et al. 2022), likely resulting from the relative dominance of hydrologic transport compared with retention of accumulated materials or combustion products. Similar to the variation in transport distances, the size and chemical composition of materials derived from burned areas influence the duration and magnitude of fire-derived signals in streams (table 2). Importantly, asynchrony between fire and precipitation in arid lands may introduce lags of months to years in the transport of materials from burned areas to streams because of episodic hydrologic connectivity (table 2; Lowman et al. 2024). The lack of hydrologic connectivity between catchments and streams also increases the cumulative transformation and removal of combustion products and materials accumulated after a fire (table 2). Finally, we hypothesize that the resilience of stream or terrestrial ecosystems to fire might limit the magnitude and duration of fire effects on streams (table 2). For example, the rapid regrowth of fire-adapted vegetation or land management could retain nutrients within catchments, stabilize soils, or moderate stream temperature (Goodridge et al. 2018, Aslan et al. 2021, Girona-García et al. 2021, Gustine et al. 2021). Within channel networks, riparian corridors might buffer streams from the effects of fire (table 2), with the caveat that geomorphic change following vegetation removal by fire or post-fire debris flows could weaken this source of resilience. In all cases, high fire severity will increase the duration and magnitude of signals, even in fire-adapted ecosystems.

Testing hypotheses to characterize mechanistic relationships and predict the effects of fire on aridland catchments requires a commitment to long-term monitoring that can capture the interactions of fire with episodic and variable precipitation. Because of the unpredictability of fires, many studies have been focused on post-fire effects, sometimes including paired monitoring of unburned catchments. This approach limits the power to separate the effects of fire from the long-term variation caused by climate and other disturbances. In regions of long return intervals for fire, where monitoring is less likely to encompass fire, a hybrid approach, pairing long-term monitoring with the initiation of post-fire monitoring in burned sites could effectively characterize both temporal variation and fire effects (Murphy et al. 2023). Experimental burning of monitored catchments could also complement this approach. Although they are costly, monitoring programs that include high-frequency observations can capture storms to increase the accuracy of estimated fluxes, resolve the effects of event timing and size, and provide insights into the accumulation and transport processes generating stream responses (Aguilera and Melack 2018a).

Given the significant spatial and temporal variation in precipitation across arid lands, monitoring networks with sites distributed along hydroclimatic, land use, productivity, and disturbance gradients (e.g., figure 2) could accelerate the discovery of mechanisms underlying the responses of aridland catchments to fire. However, consistent funding remains a barrier to research based on long-term monitoring (Hughes et al. 2017). Effective and timely analyses can best leverage monitoring data. We suggest that statistical modeling approaches addressing multiscale temporal patterns can deliver insights relevant to multiple phenomena or ecosystem services (e.g., Lowman et al. 2024). In addition, investigating feedbacks and their potential context dependence must characterize nonlinear relationships (e.g., convergent cross-mapping analysis; Sugihara et al. 2012), but such analytical tools require support from rich time series. Data from long-term monitoring might also be used to parameterize process-oriented models for predicting stochastic outcomes resulting from nonlinear interactions among accumulation, combustion, transport, and propagation. In addition to the discharge and material concentrations in streams, remotely sensed measures of vegetation (e.g., LiDAR, synthetic aperture radar; Loudermilk et al. 2009), fire intensity, and ash deposition (e.g., hyperspectral observations; Goodridge et al. 2018) could support models of vegetation regrowth, routes of hydrologic transport, and estimates of material stores within soils and vegetation. For example, numerical experiments could assess the interactions of fire intensity with the rates of vegetation growth and the routing of water through the uplands to predict material transport to streams.

The increasing frequency, intensity, and size of fires occurring in arid lands is accelerating change to ecosystems and the ecosystem services that support human populations. Intermittent hydrologic connectivity, large event-scale loads, and potential for long-range hydrologic transport contribute greater uncertainty in the timing, duration, and types of fire effects on aridland streams compared with mesic counterparts. We propose that a catchment perspective can contribute to building mechanistic understanding of the effects of fire on aridland ecosystems both by discerning potential effects on aquatic ecosystems and water supplies and by contributing potentially novel insights regarding terrestrial processes that are observable from patterns in stream hydrology and chemistry. Aridland regions are characterized by high spatial and temporal variation in precipitation regimes; therefore, resolving the role of hydroclimate in catchment responses to fire is a central research priority.

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